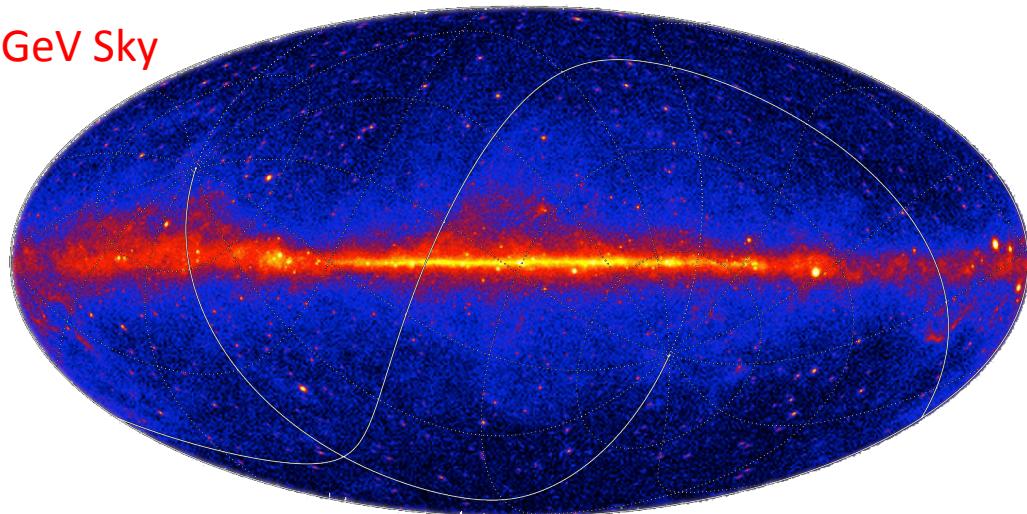
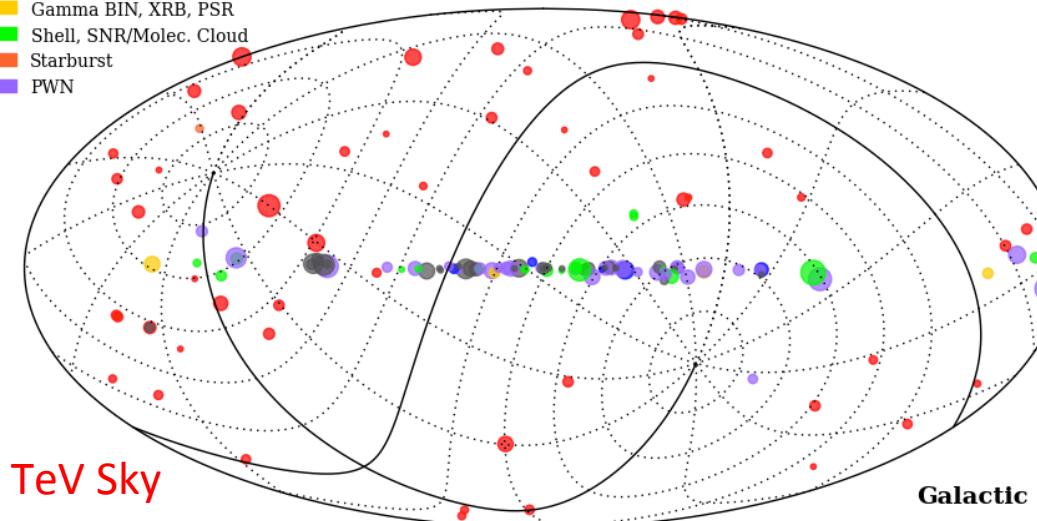


Context: the GeV-TeV Sky

GeV Sky

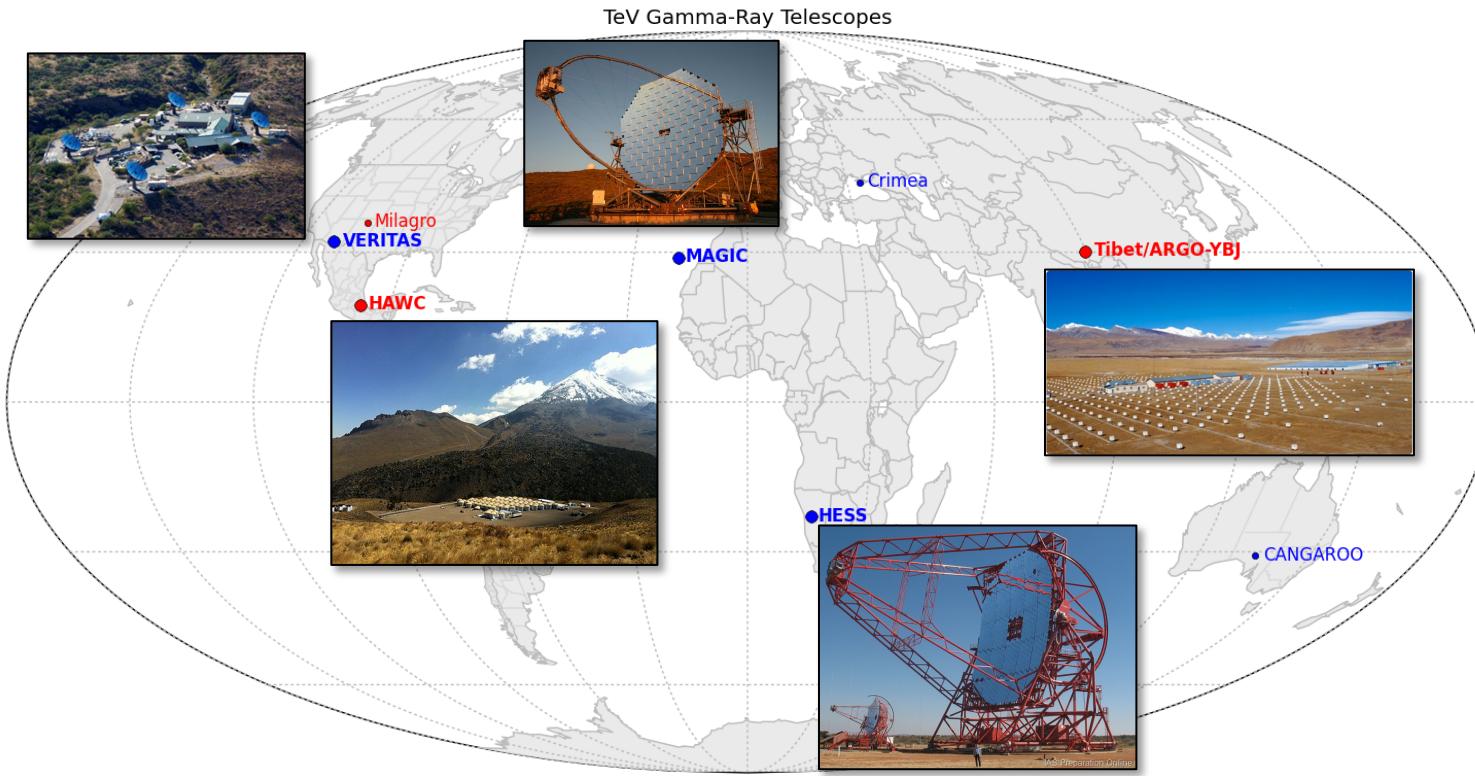


- UNID, DARK
- Star Forming Region, Cat. Var., Globular Cluster, Massive Star Cluster
- HBL, IBL, FSRQ, FRI, AGN (unknown type), LBL
- Gamma BIN, XRB, PSR
- Shell, SNR/Molec. Cloud
- Starburst
- PWN



- **GeV Band**
 - 2000 point sources
 - Diffuse emission
- **TeV Band**
 - About 150 point sources
 - Few diffuse measurements (Milagro)
- Motivation for **synoptic survey** at TeV

TeV Observatories



- *Telescopes: low uptime, small FOV, excellent bkg rejection -> deep surveys, point sources, high-resolution energy spectra*
- *Arrays: high uptime, large FOV -> unbiased surveys, transients, extended/diffuse emission, cosmic rays and solar physics*



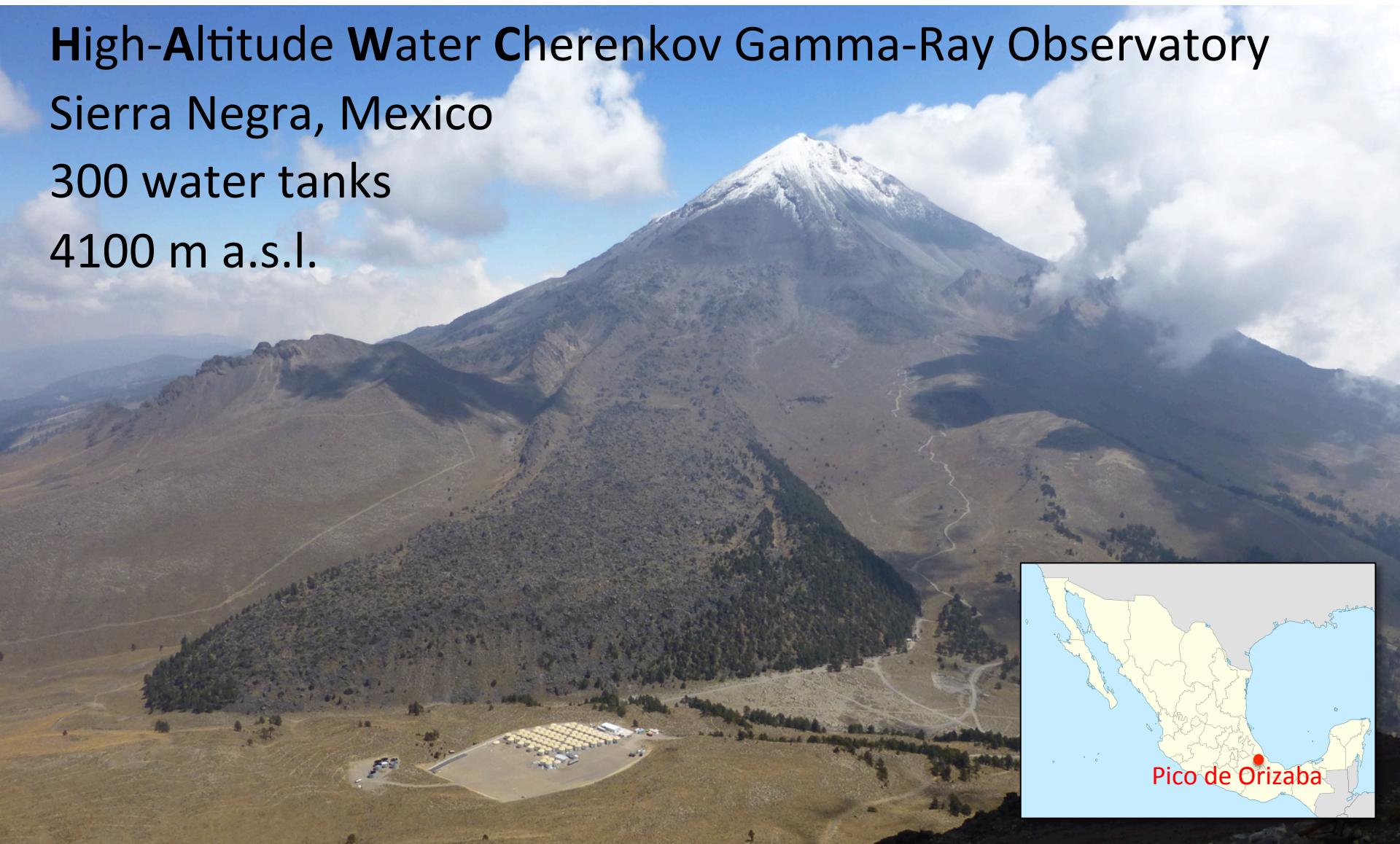
The HAWC Observatory

High-Altitude Water Cherenkov Gamma-Ray Observatory

Sierra Negra, Mexico

300 water tanks

4100 m a.s.l.

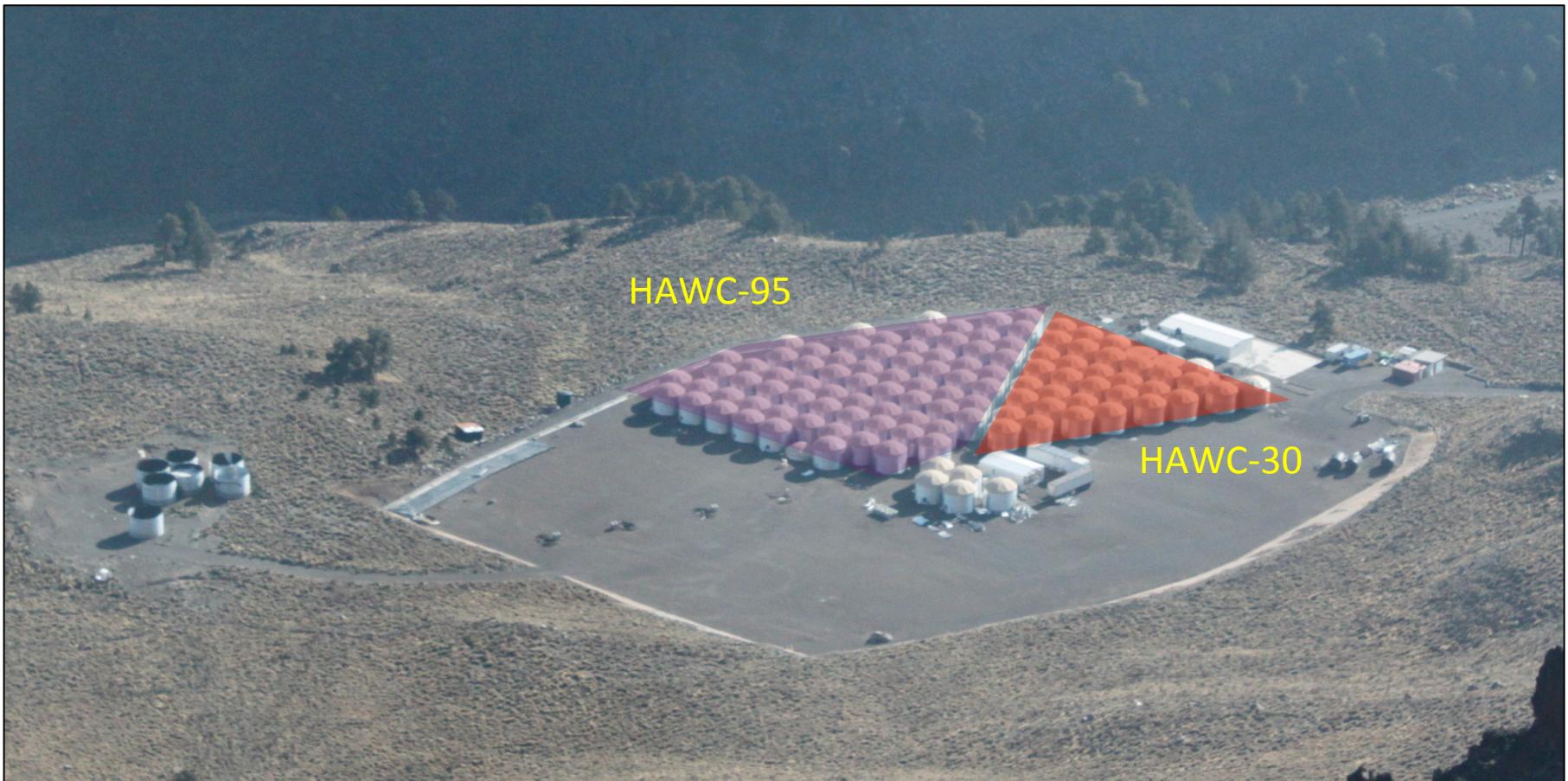


HAWC Collaboration



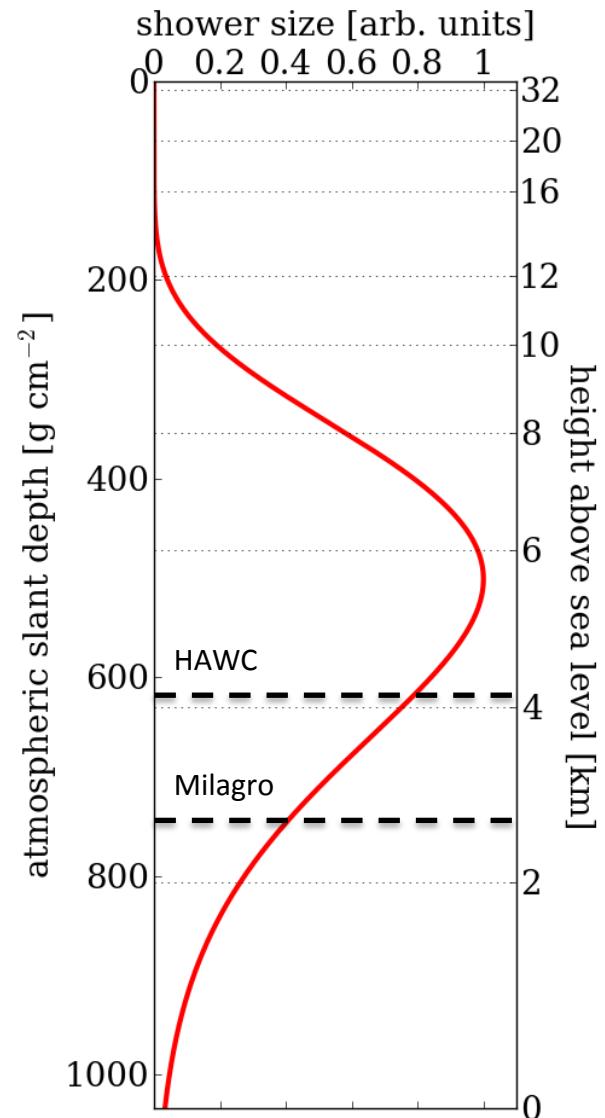
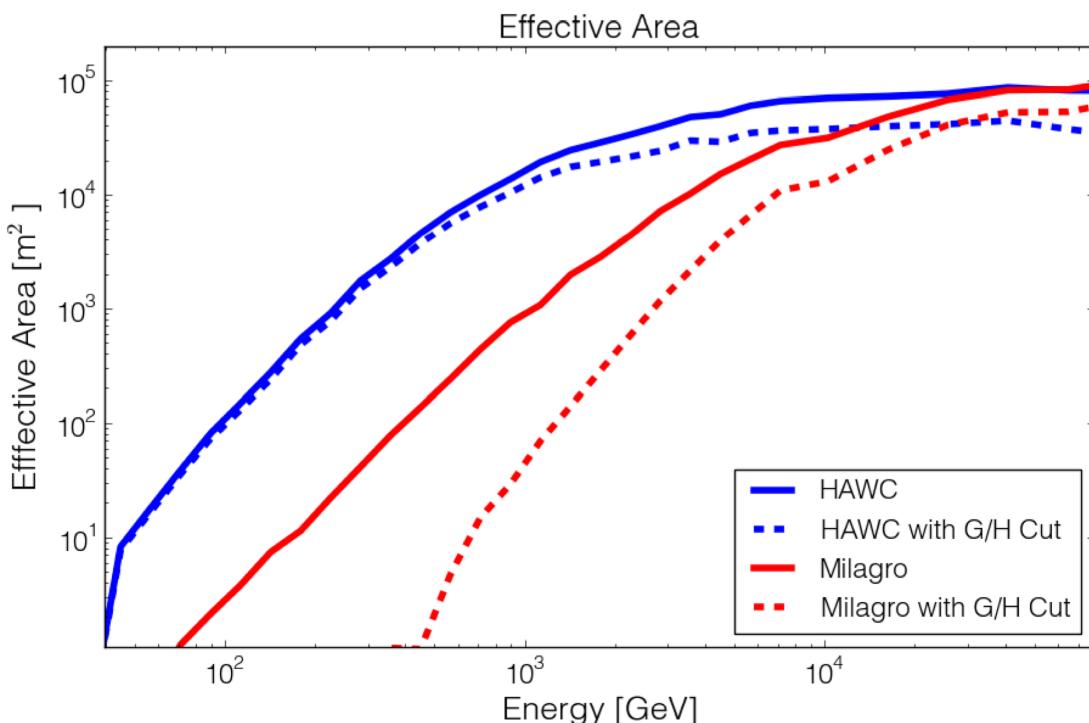
HAWC-30 Detector

- Operated with **30 tanks**: Oct 2012 – Apr 2013
- 111 tanks in DAQ Aug 2013; 300 tanks, Sep 2014



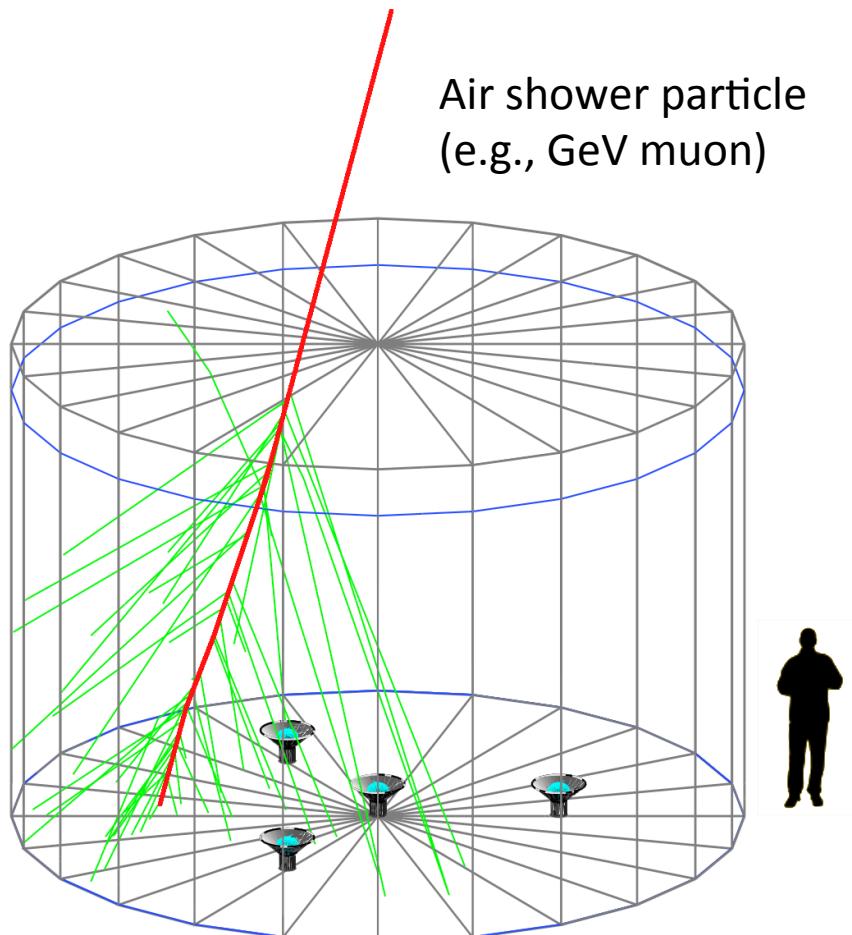
High Altitude...

- Goal of HAWC: observe gamma-ray and cosmic-ray air showers from **half the sky**
- High altitude: gain significant sensitivity **below 1 TeV**



...Water Cherenkov

- Water Cherenkov array: proven technique, e.g. Milagro

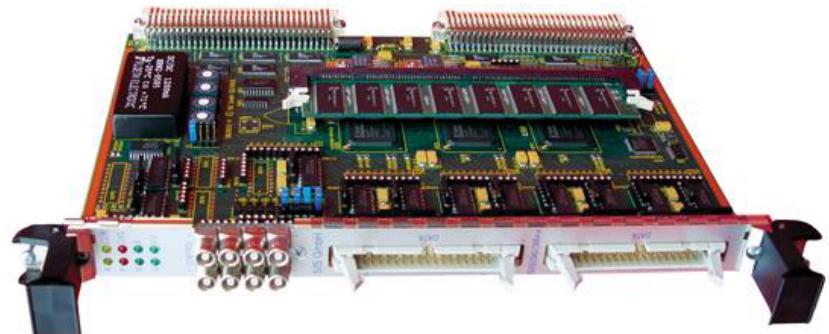
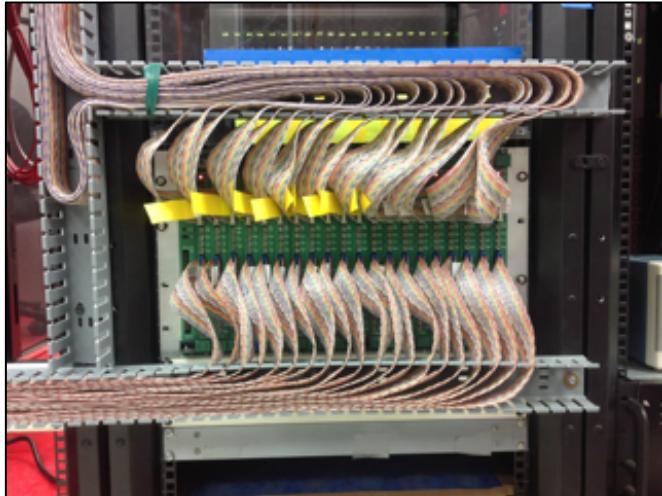


- 300 tanks: **5 m x 7.3 m**
- 200 kL of purified water
- 3x Hamamatsu **R5912 (8")**,
1x **R7081 (10")**



Data Acquisition System

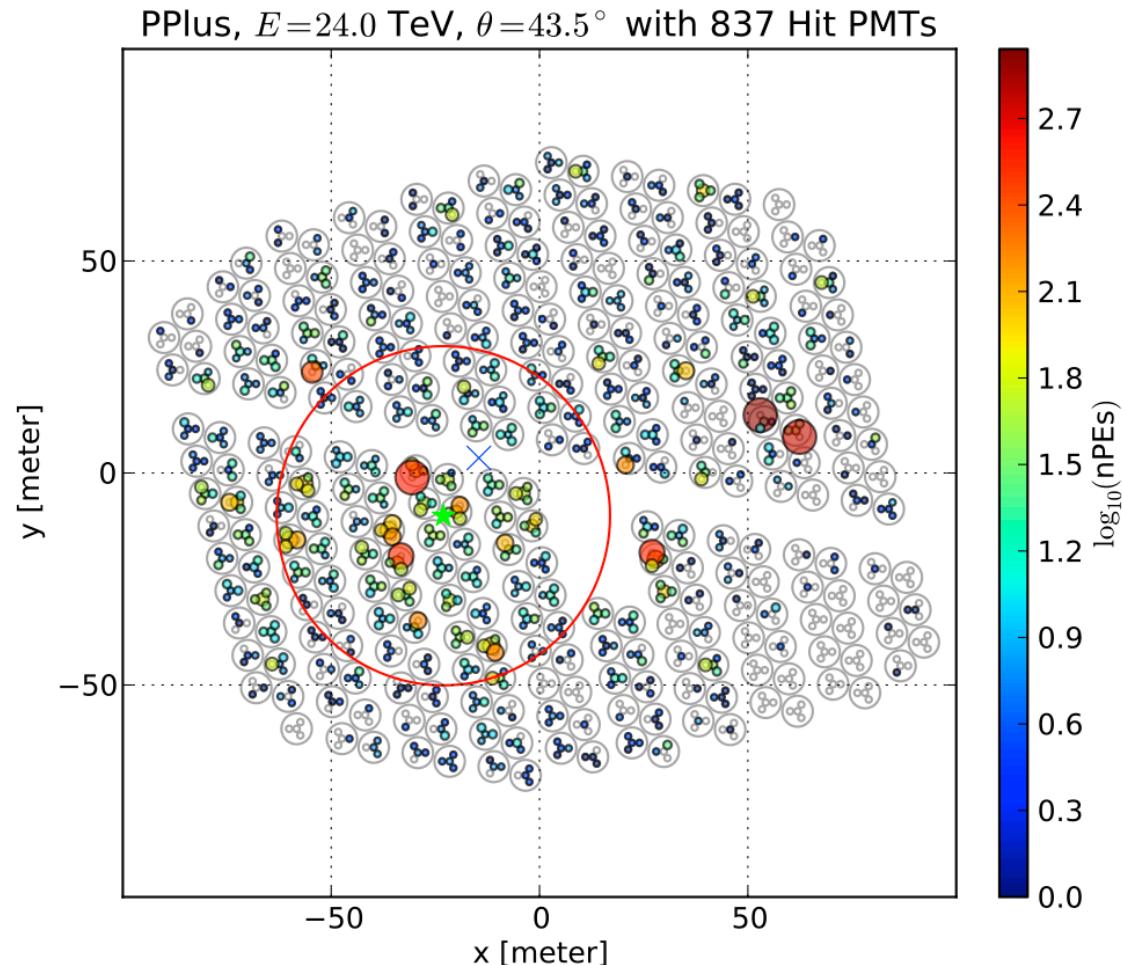
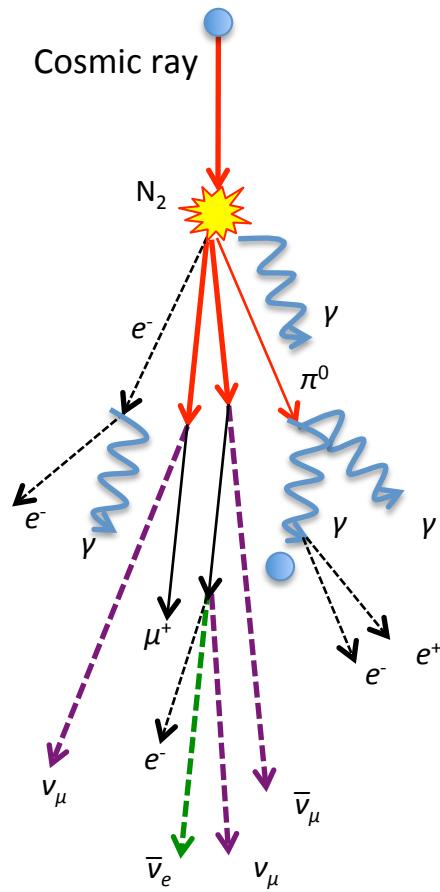
- Triggered DAQ
 - Software trigger with simple multiplicity condition
 - $A_{\text{eff}} = 100 \text{ m}^2$ @ 100 GeV
- Scaler DAQ
 - Independent readout (monitoring)
 - PMT pulse counting, no event geometry
 - $A_{\text{eff}} = 10^4 \text{ m}^2$ @ 100 GeV



A.U. Abeysekara et al., Astropart. Phys. 35:641, 2012

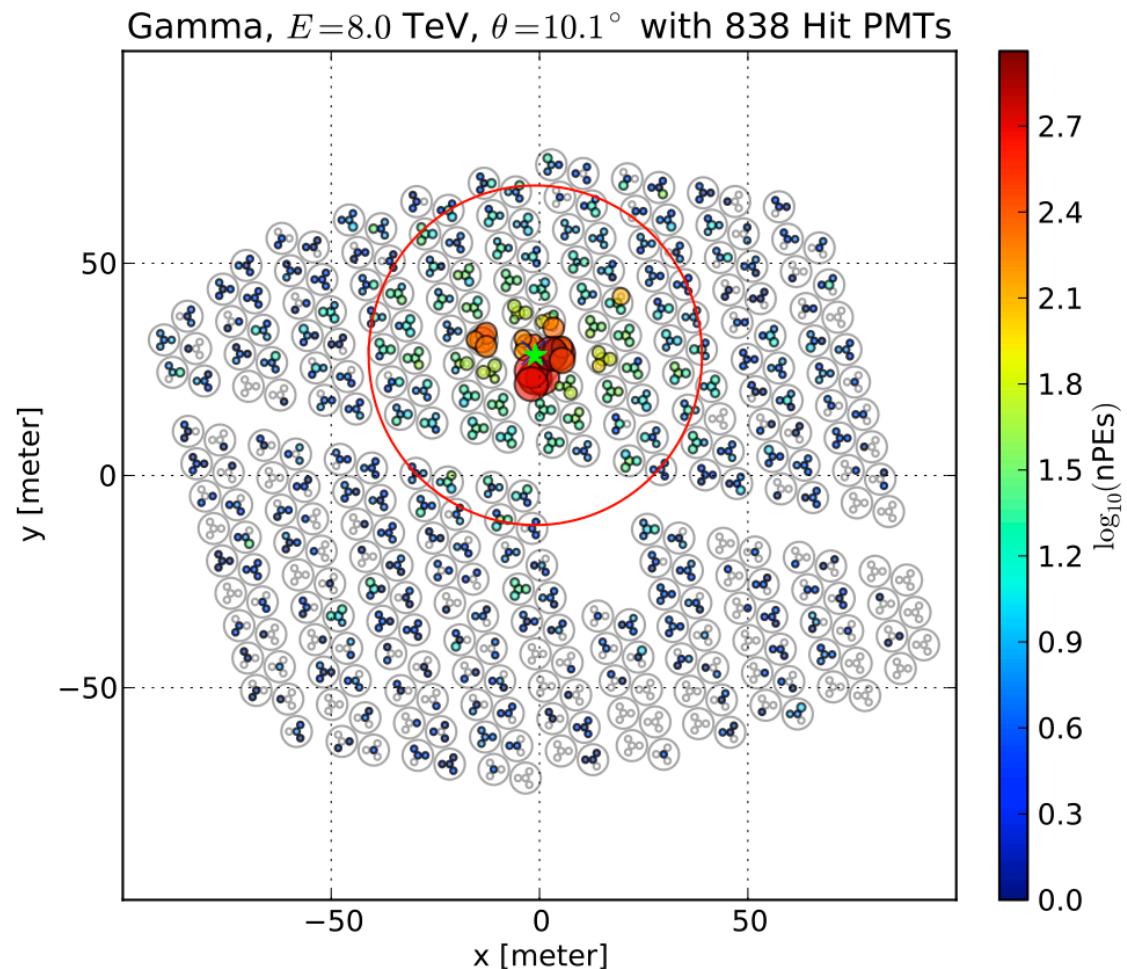
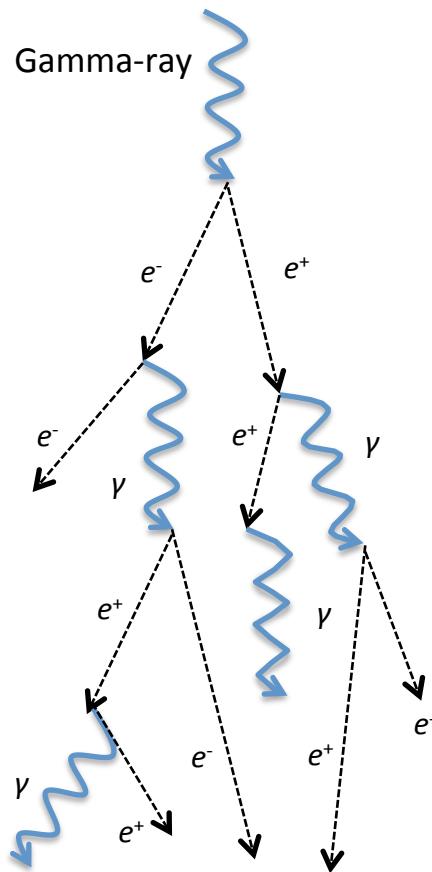
Background: Proton Tagging

- Look for large hits far from core (**99% @ 10 TeV**)



Signal: Gamma-Ray Tagging

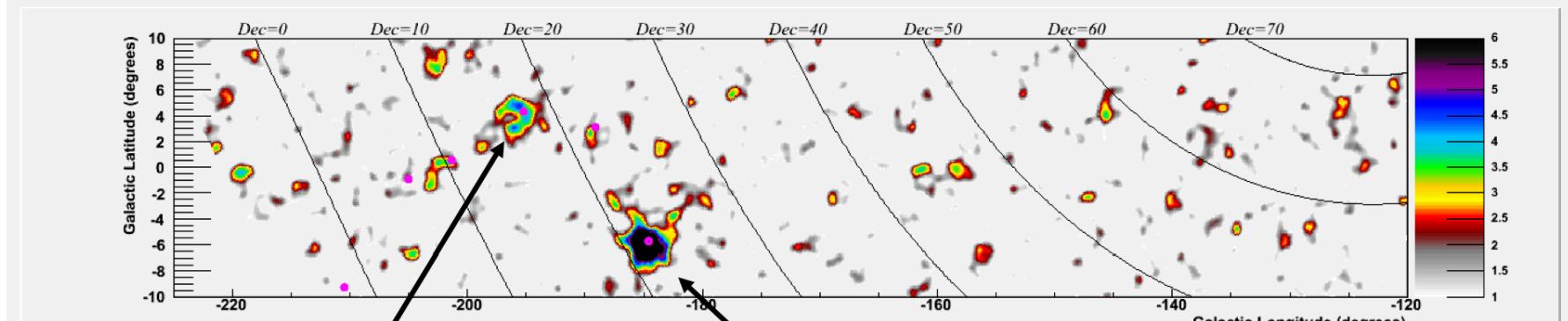
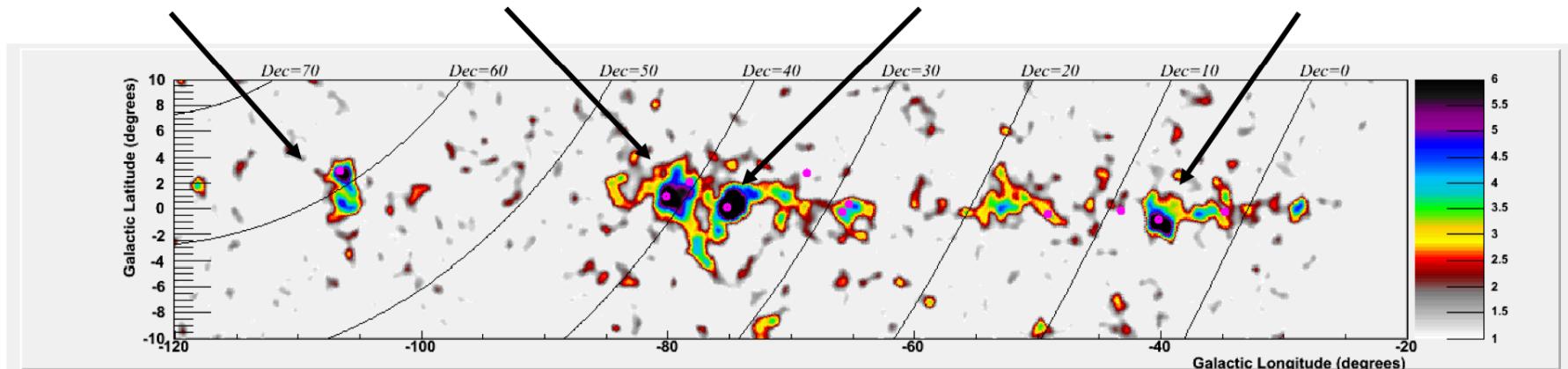
- Proton cut: removes 50% of gammas @ 10 TeV



Milagro: Galactic Plane Survey

- Milagro was an excellent **survey instrument**
- **Galactic plane:** A. Abdo et al., ApJ **688:1078** (2008)

Boomerang PWN MGRO J2032+41 MGRO J2019+37 MGRO J1908+06

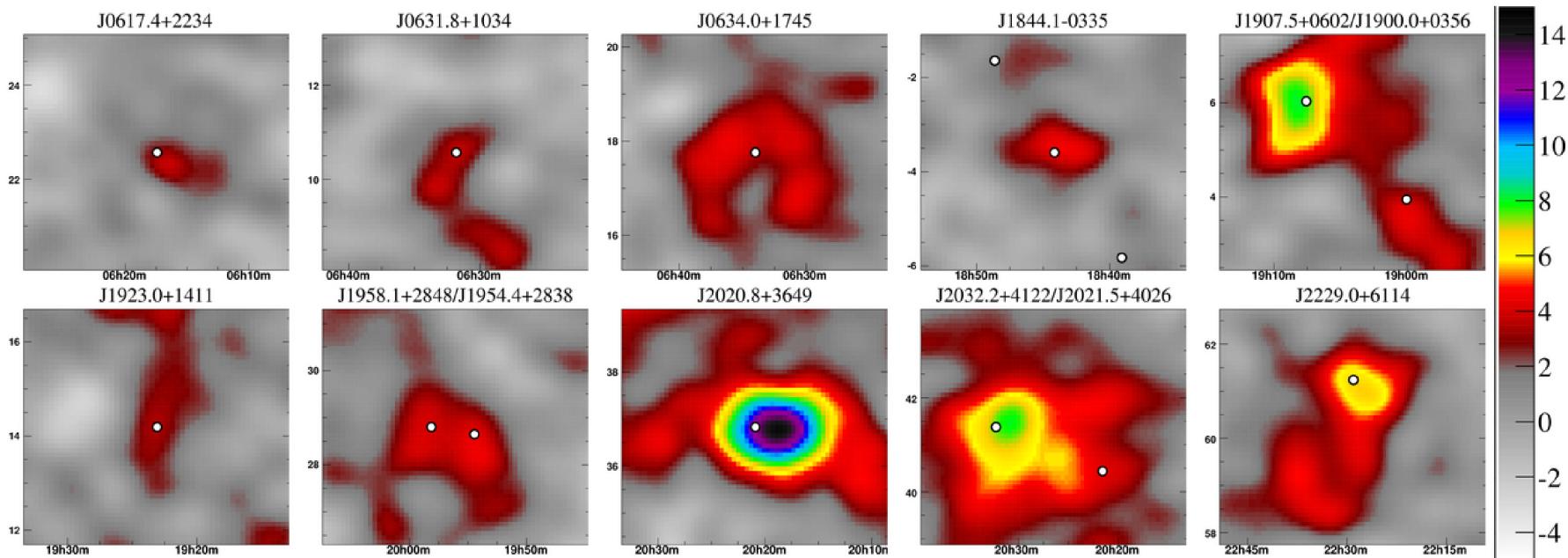


Geminga

Crab

Milagro: Fermi Bright Source List

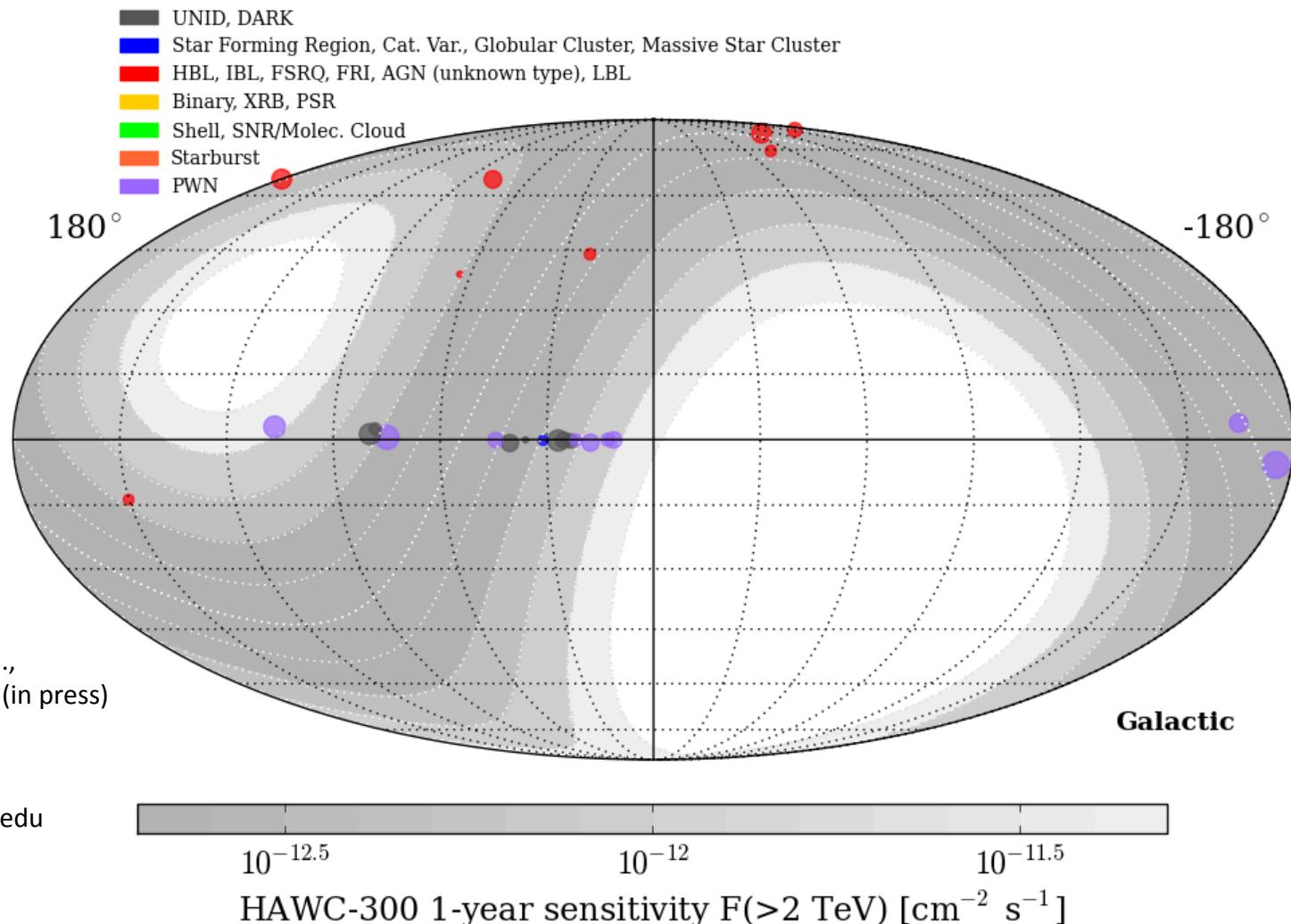
- TeV observations of the brightest GeV sources with Milagro: A. Abdo et al., ApJ 700:L127 (2009)



- Some sources are extended over **several degrees**
- Potentially many sources below Milagro threshold

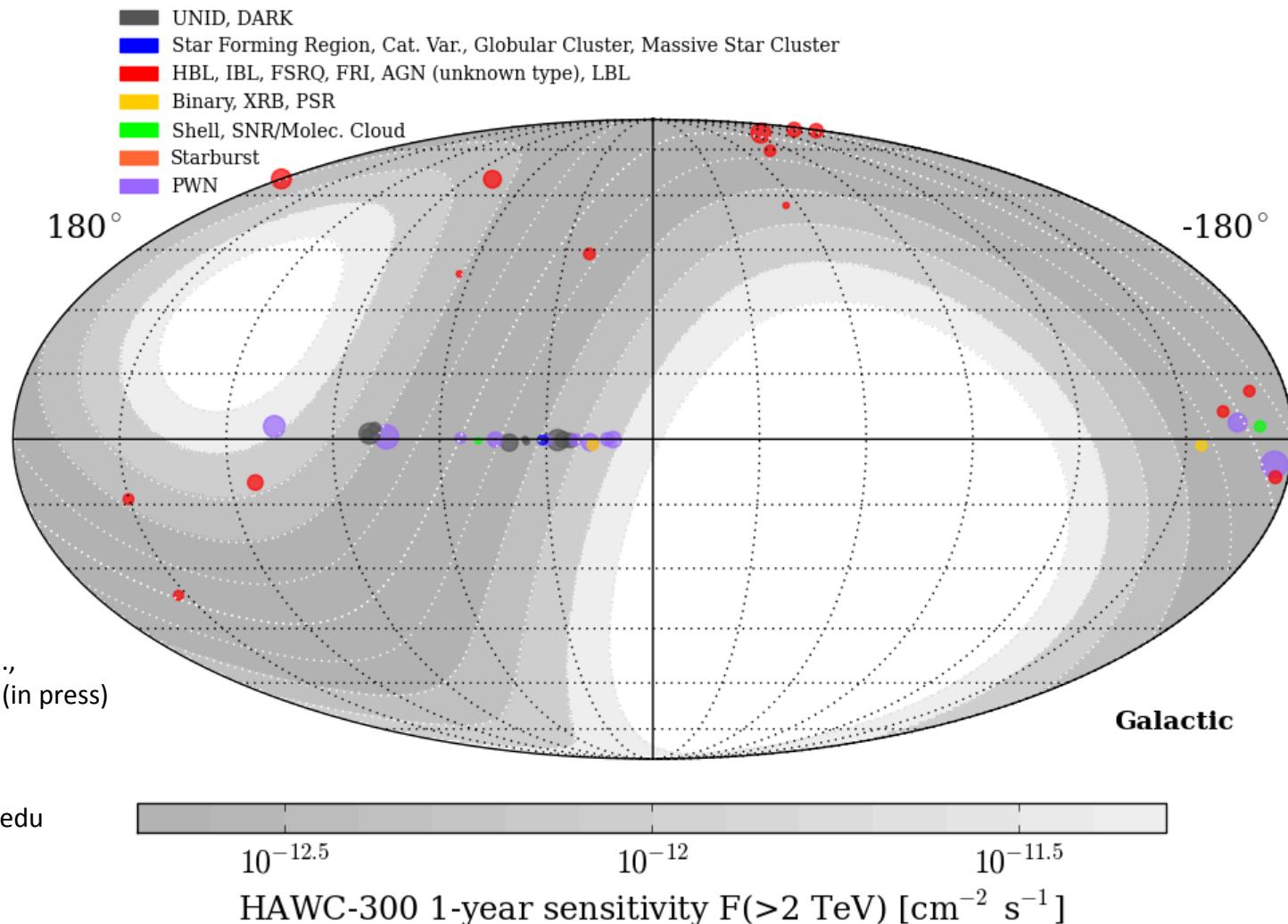
Synoptic Survey of TeV Sky

- 25 *known sources* at $>5\sigma$ after 1 year (quiescent)



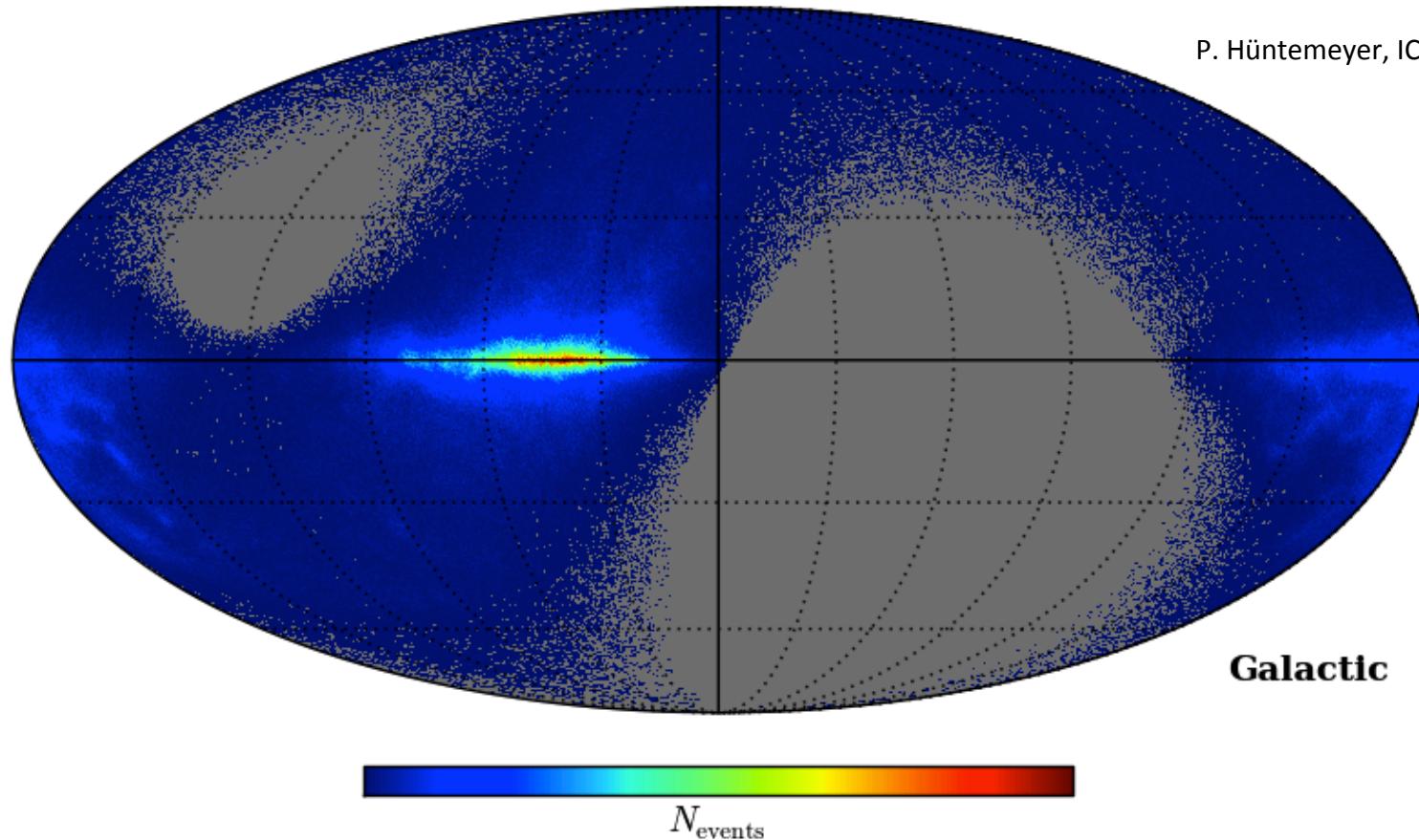
Synoptic Survey of TeV Sky

- 40 *known sources* at $>5\sigma$ after 5 years (quiescent)



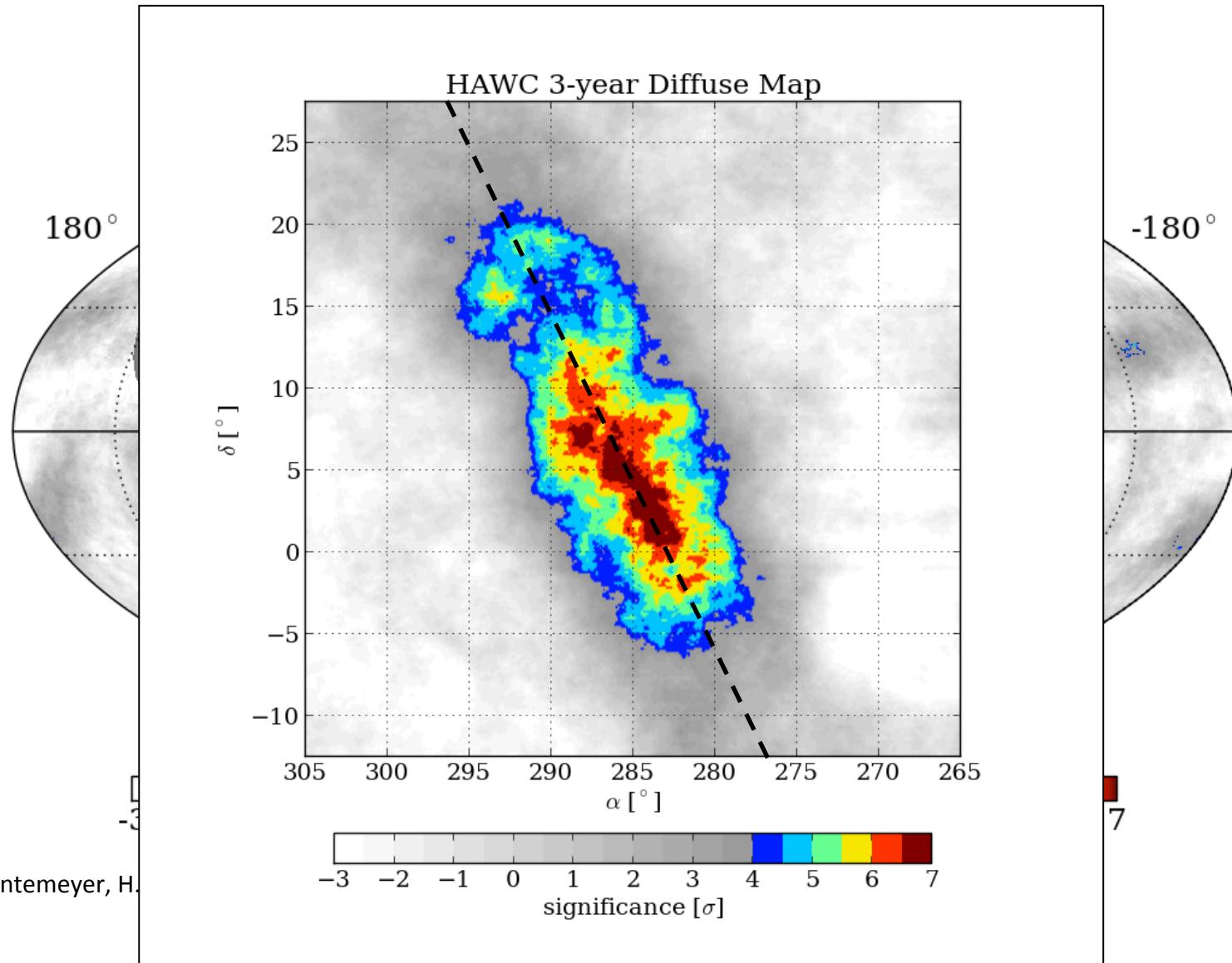
Galactic Diffuse Emission

- Simulated events in HAWC-300 from **ICS + brem + π^0**



- GALPROP GeV extrapolation (under-predicts Milagro)

Observation of Diffuse Emission



P. Hüntemeyer, H.

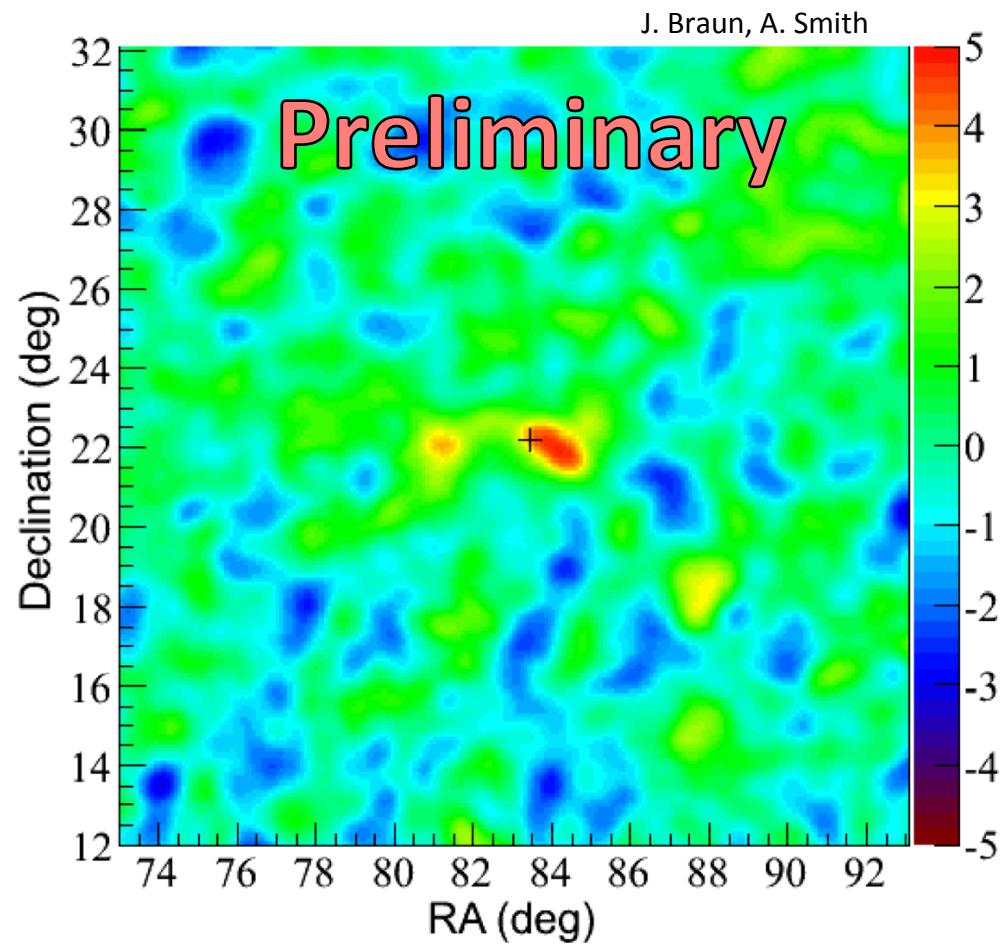
Measurements

- Crab Nebula: data from HAWC-95
- Transients: GRB 130427A
- Cosmic Rays: moon shadow, sun shadow, anisotropy

Measurements of Crab Nebula

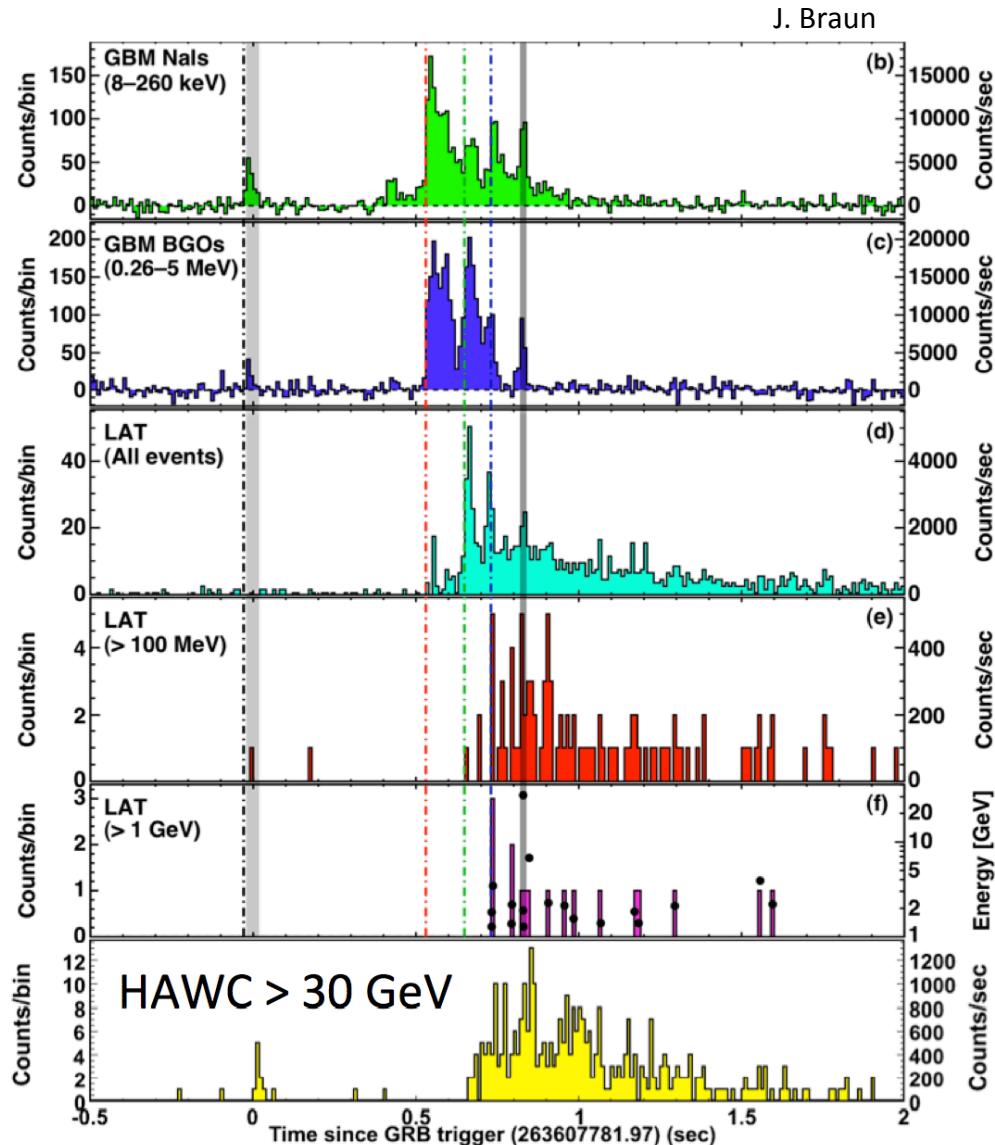
- Strongest TeV source, transits near detector zenith
- HAWC-95 (Jun 14-Aug 2): 4.8σ
- Note: PMT calibration **not yet applied**

Geometry	Date	1 Crab
HAWC-30	Oct. 2012	--
HAWC-111	Aug. 2013	14 transits
HAWC-300	Sep. 2014	<1 transit

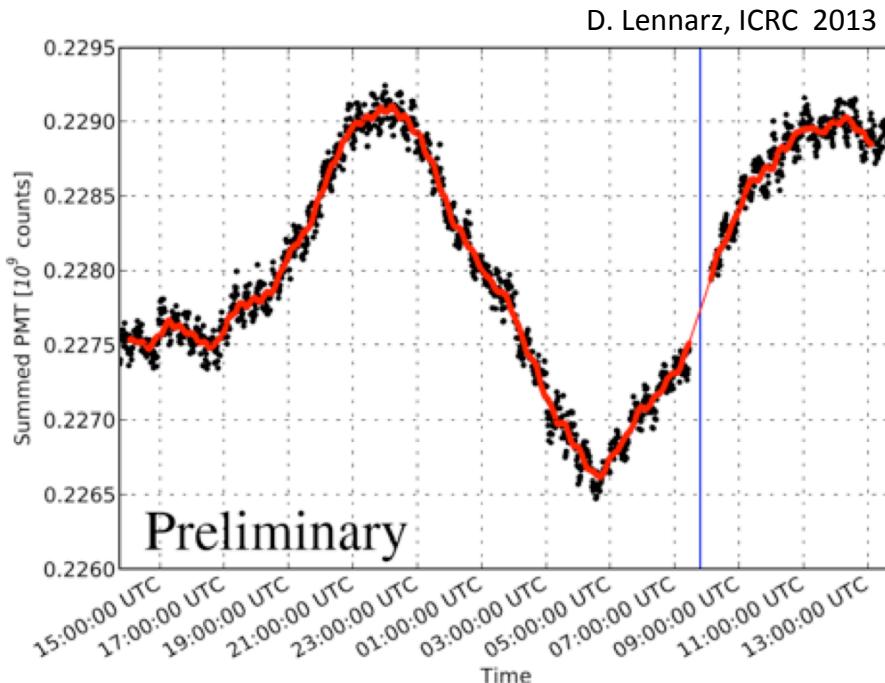
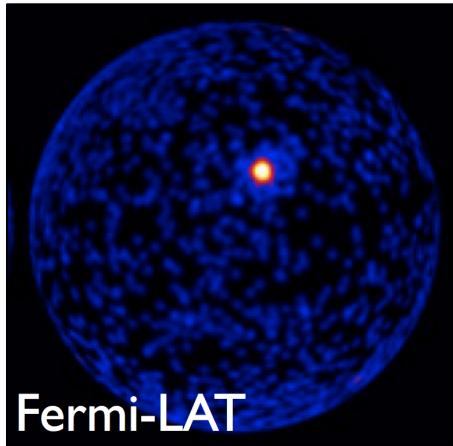


Observations of Transient Sources

- Upper limit on GRB rate:
1.65 yr⁻¹ in coincidence
with Fermi-GBM
(Taboada and Gilmore,
arXiv:1306.1127)
 - Just need to wait for a
bright GRB
 - E.g., GRB 090510
spectrum, if extended to
125 GeV, yields **200**
photons above 30 GeV



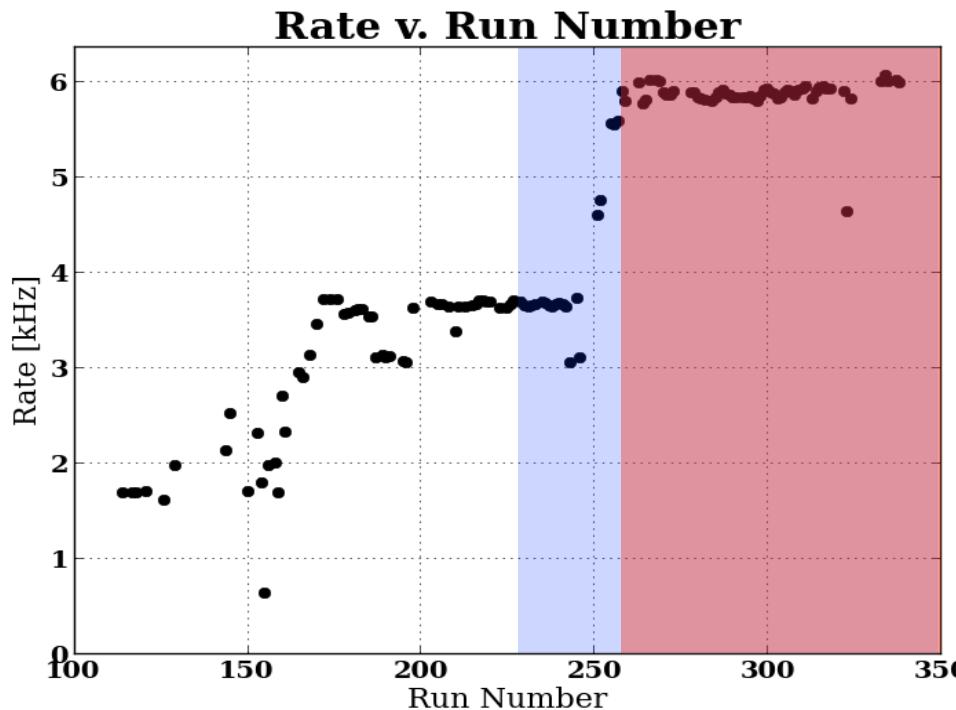
GRB 130427A: HAWC-30



- Extremely bright source:
 - 2×10^{-3} erg cm⁻² (highest in 30 years)
 - 94 GeV photon observed
- HAWC measurement:
 - Main DAQ off
 - Scaler DAQ on
 - GRB @ 57° zenith and *setting*
- No signal in 6 time windows (GCN Circular 14549)
- Would be $\sim 5\sigma$ if near zenith

HAWC-30 Cosmic-Ray Data Set

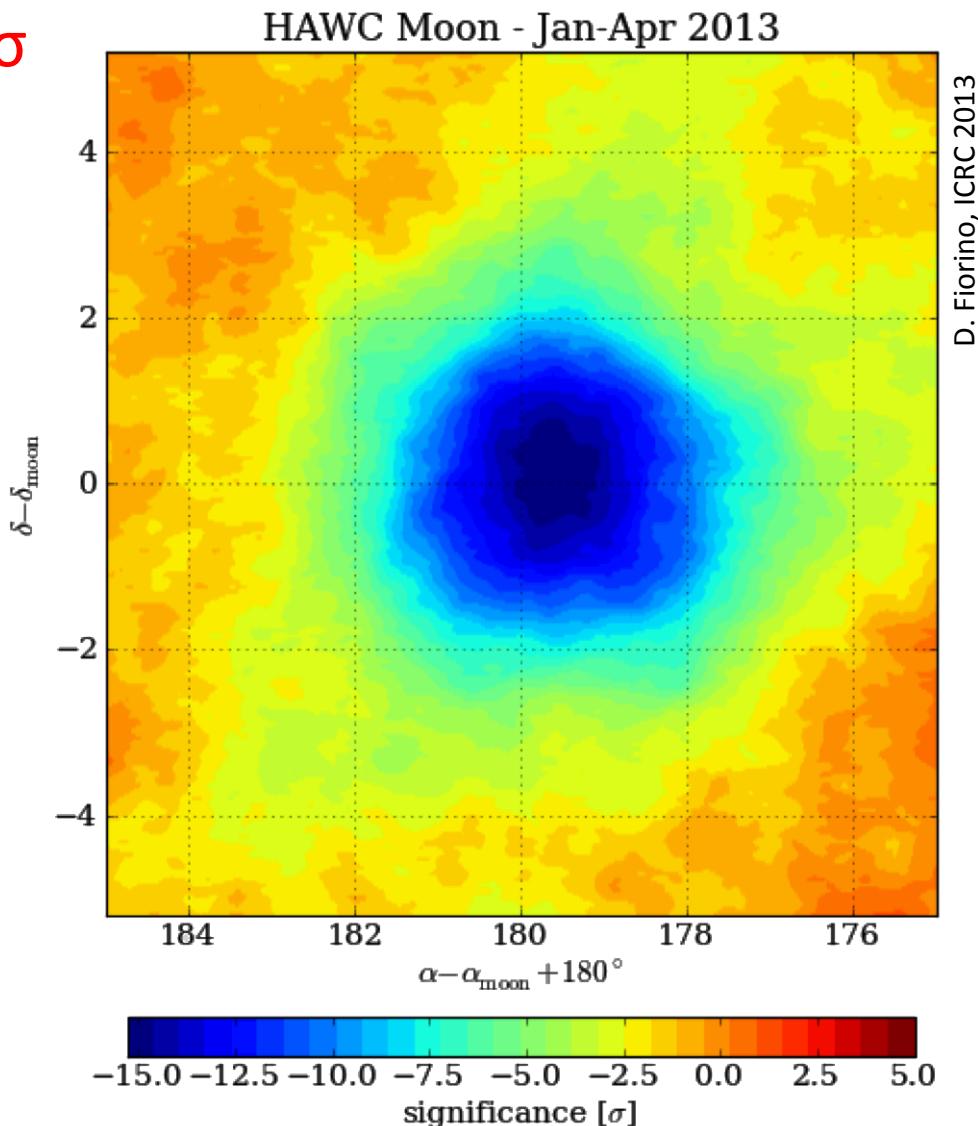
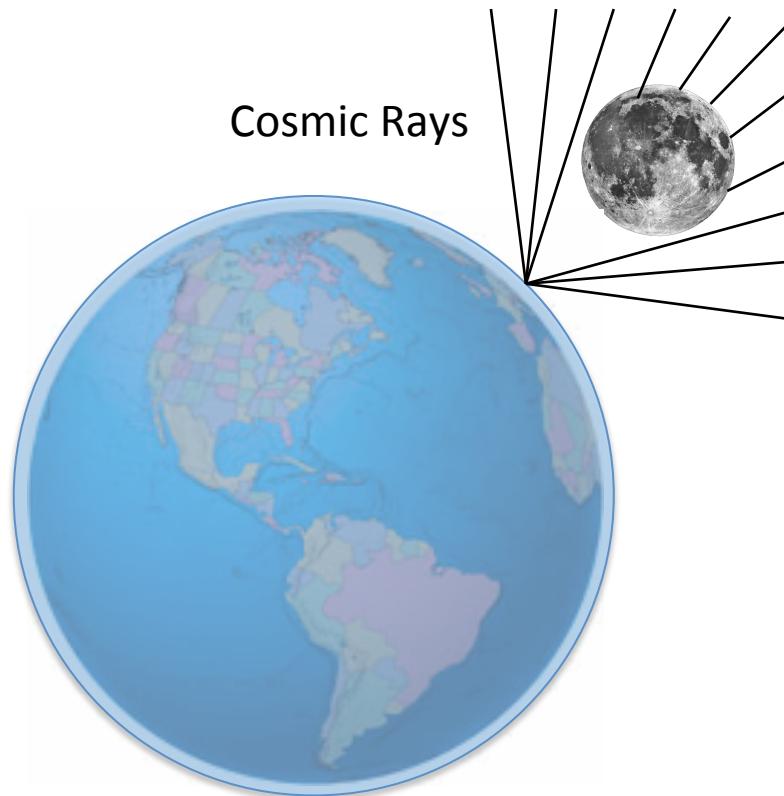
- Livetime: **95 days** (2273.8 hr) livetime between Jan. 1 – Apr. 15, 2013
- Event rate ~ 6 kHz; 2.1×10^{10} events in data sample



- Angular resolution: **1.5°**. Median energy: **2 TeV**

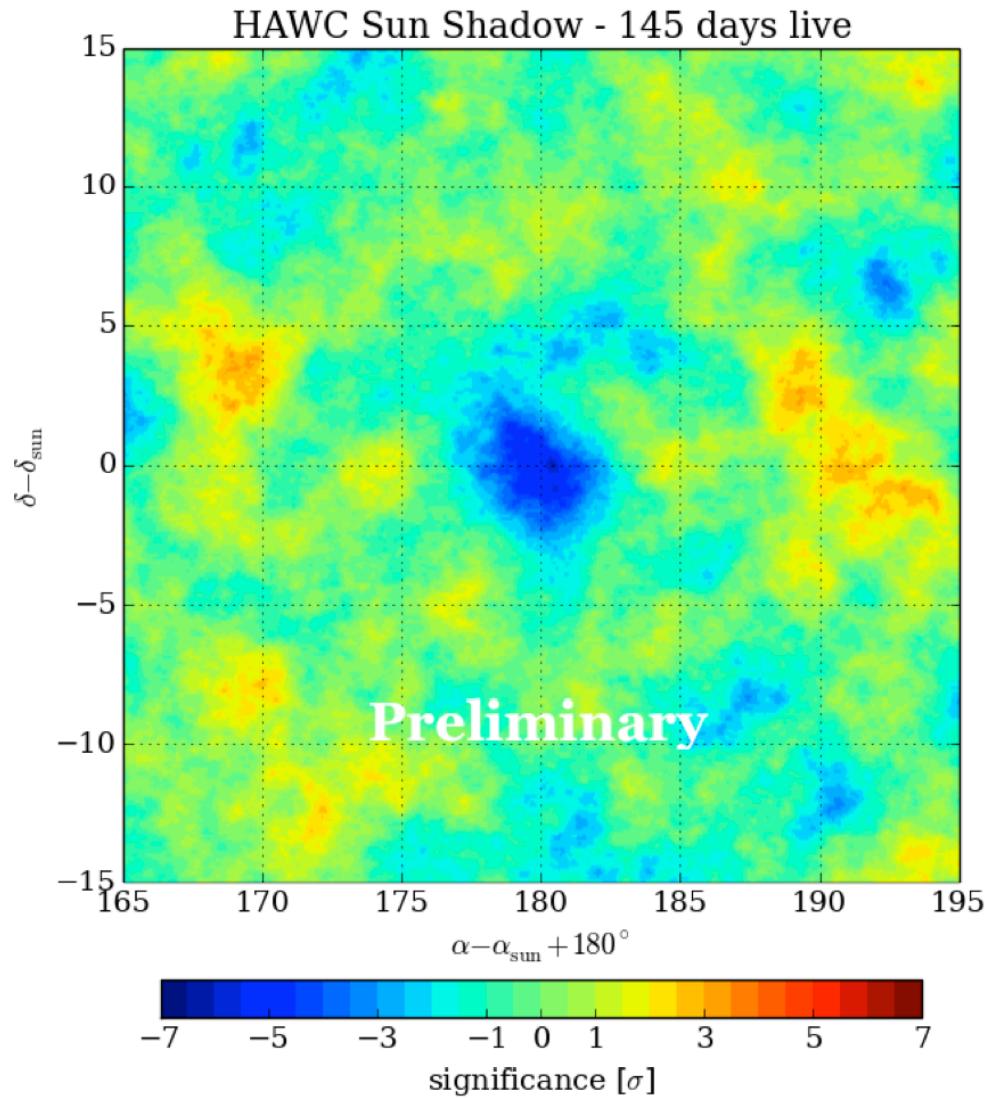
Moon Shadow in Cosmic Rays

- Shadow observation: -15.5σ
- Position is consistent with geomagnetic deflection

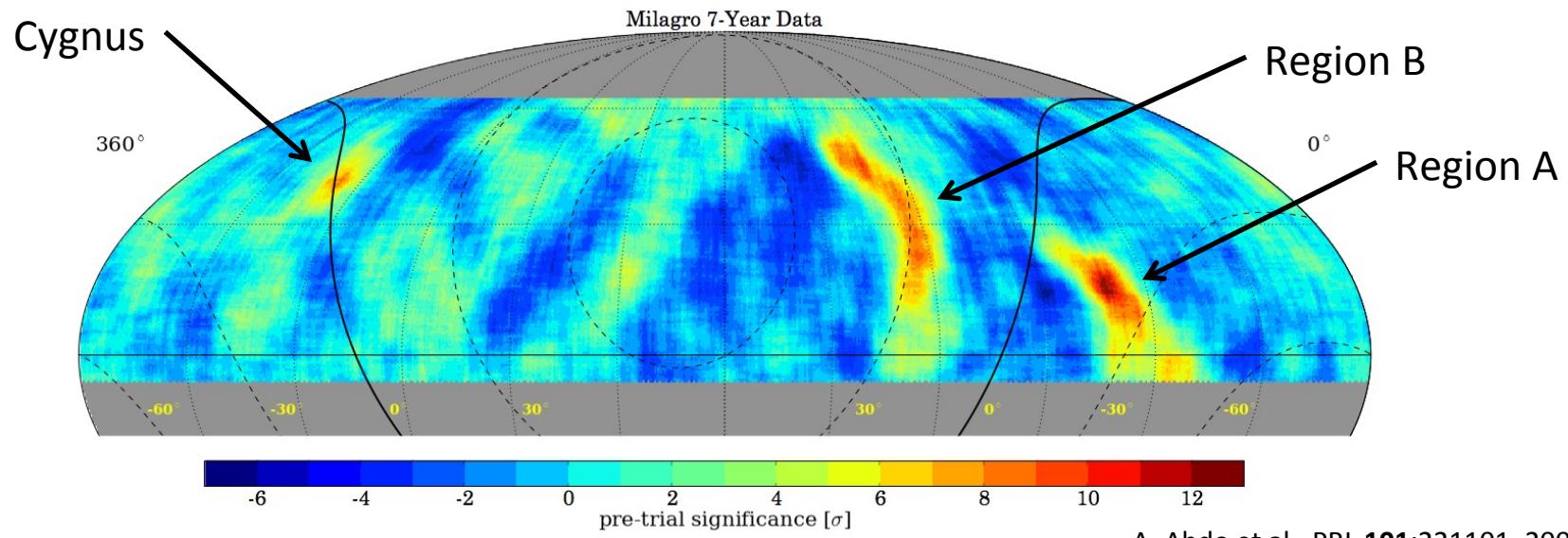


Sun Shadow in Cosmic Rays

- Sun shadow also observed (-6.4σ) with HAWC-30
- Shadow offset is **consistent with geomagnetic deflection**
- Amplitude consistent with expectations for this part of the solar cycle
- Physics: magnetic field in solar corona



Cosmic Ray Anisotropy: Milagro

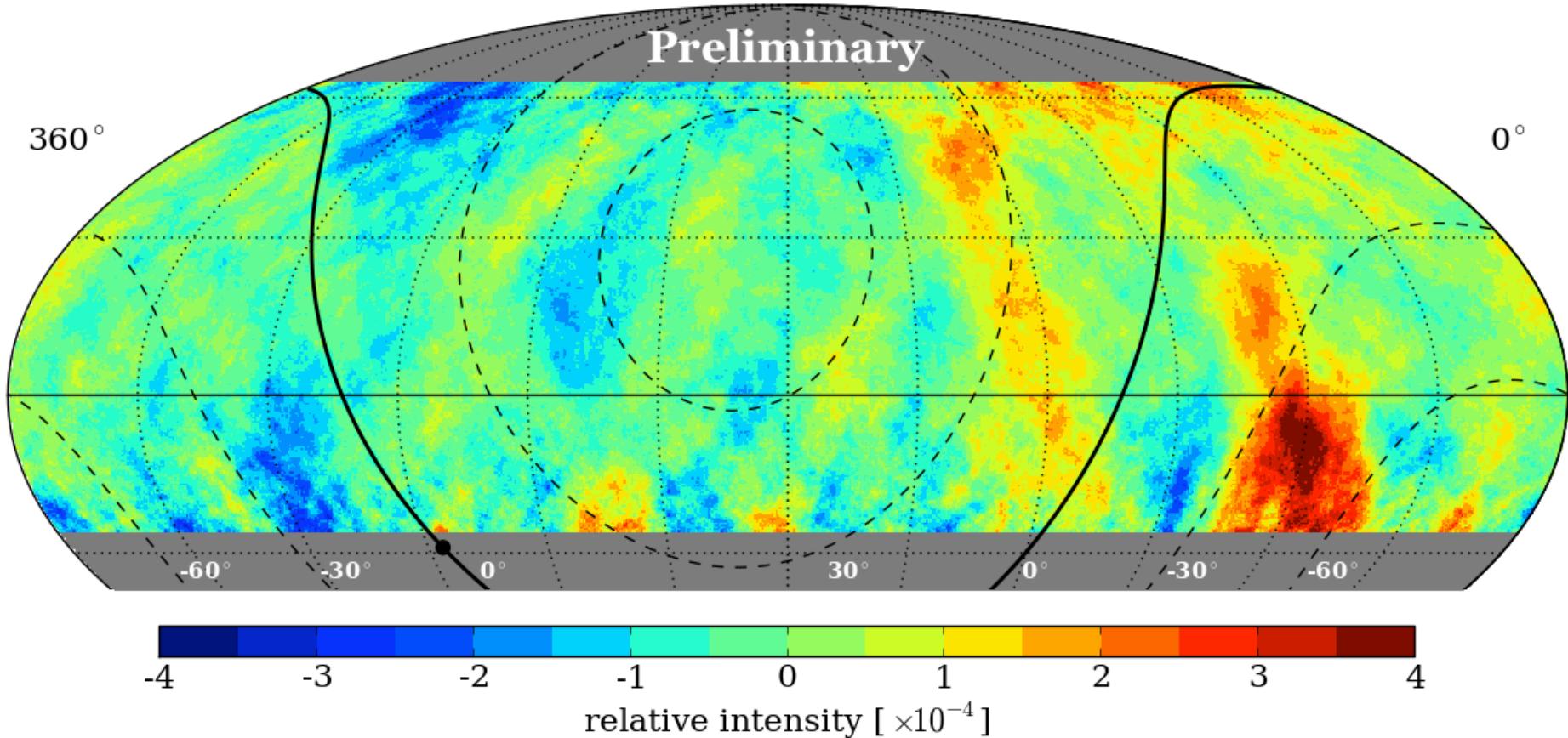


- Magnetic scattering?
 - Malkov et al., ApJ **721**:750, 2010
 - Giacinti et al., PRL **109**:071101, 2012
- More exotic?
 - Stranglet spallation: K. Kotera et al., Phys. Lett. B **725**:196, 2013
 - DM: J.P. Harding, arXiv:1307.6537

Small-Scale Structure with HAWC

- Relative intensity $\delta I_i(\alpha, \delta) = \frac{\Delta N_i}{\langle N \rangle} = \frac{N_i(\alpha, \delta) - \langle N_i(\alpha, \delta) \rangle}{\langle N_i(\alpha, \delta) \rangle}$

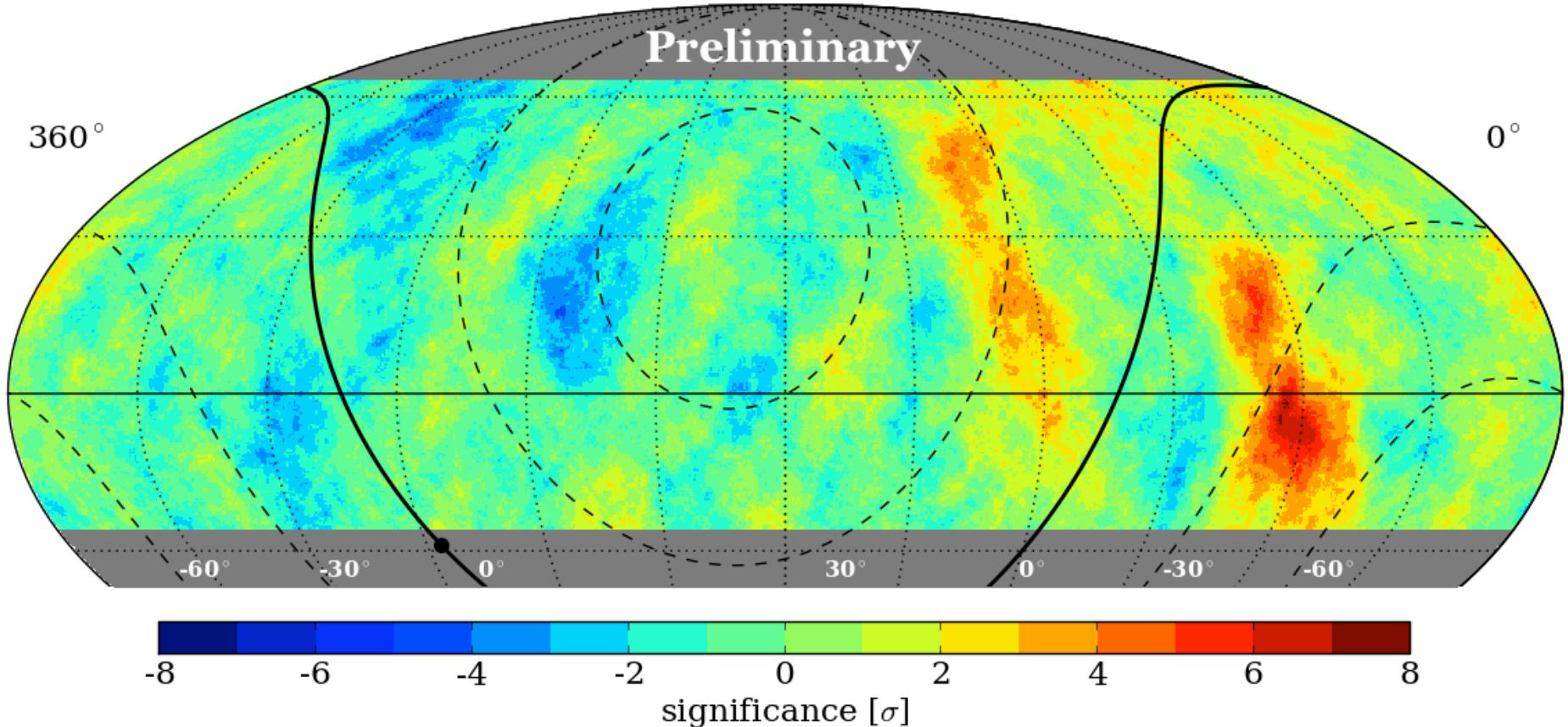
HAWC-30: 1 Jan 2013 - 15 Apr 2013, 10° Smoothing



Small-Scale Structure

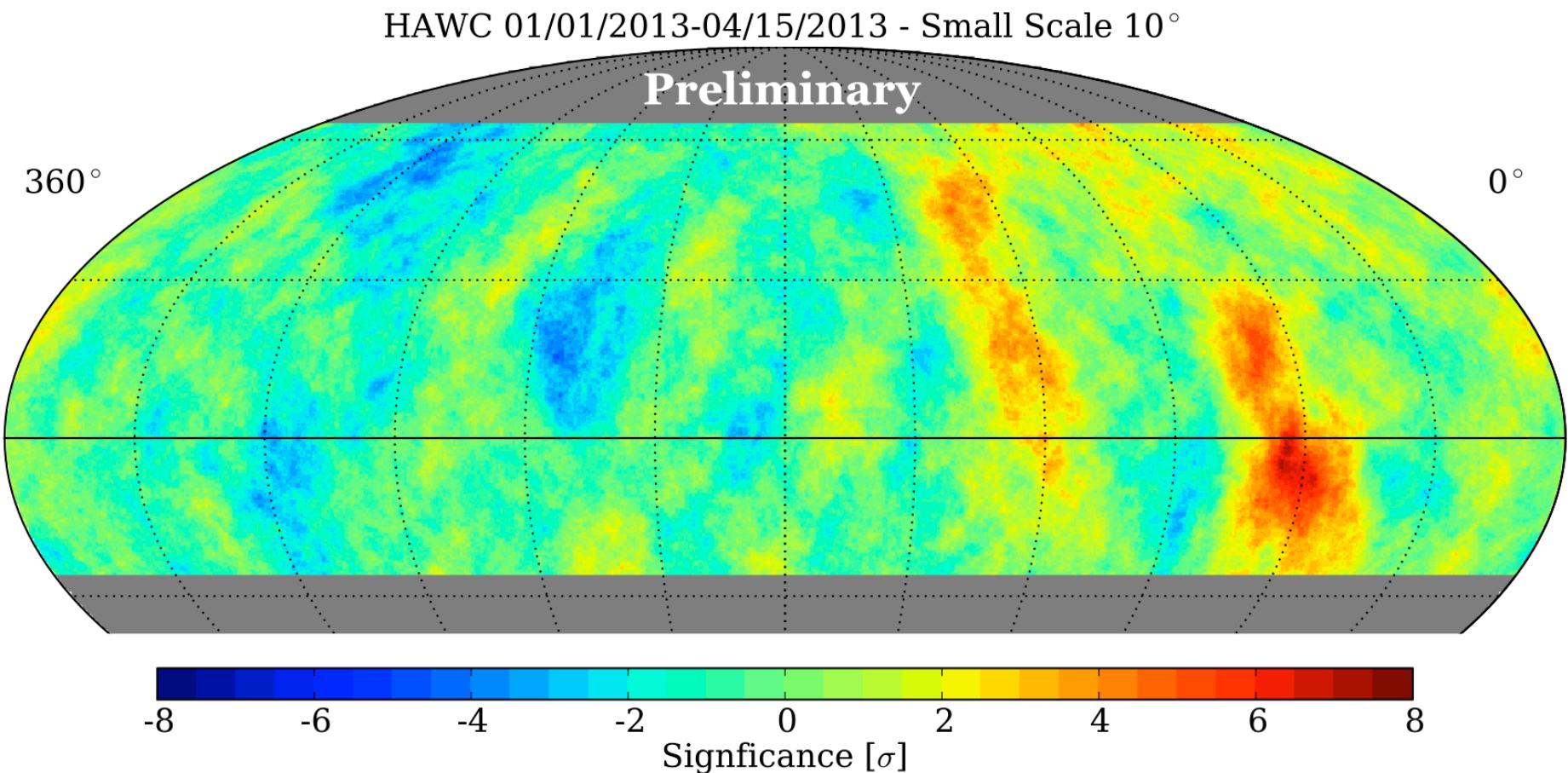
- Significance (before trials):

HAWC-30: 1 Jan 2013 - 15 Apr 2013, 10° Smoothing



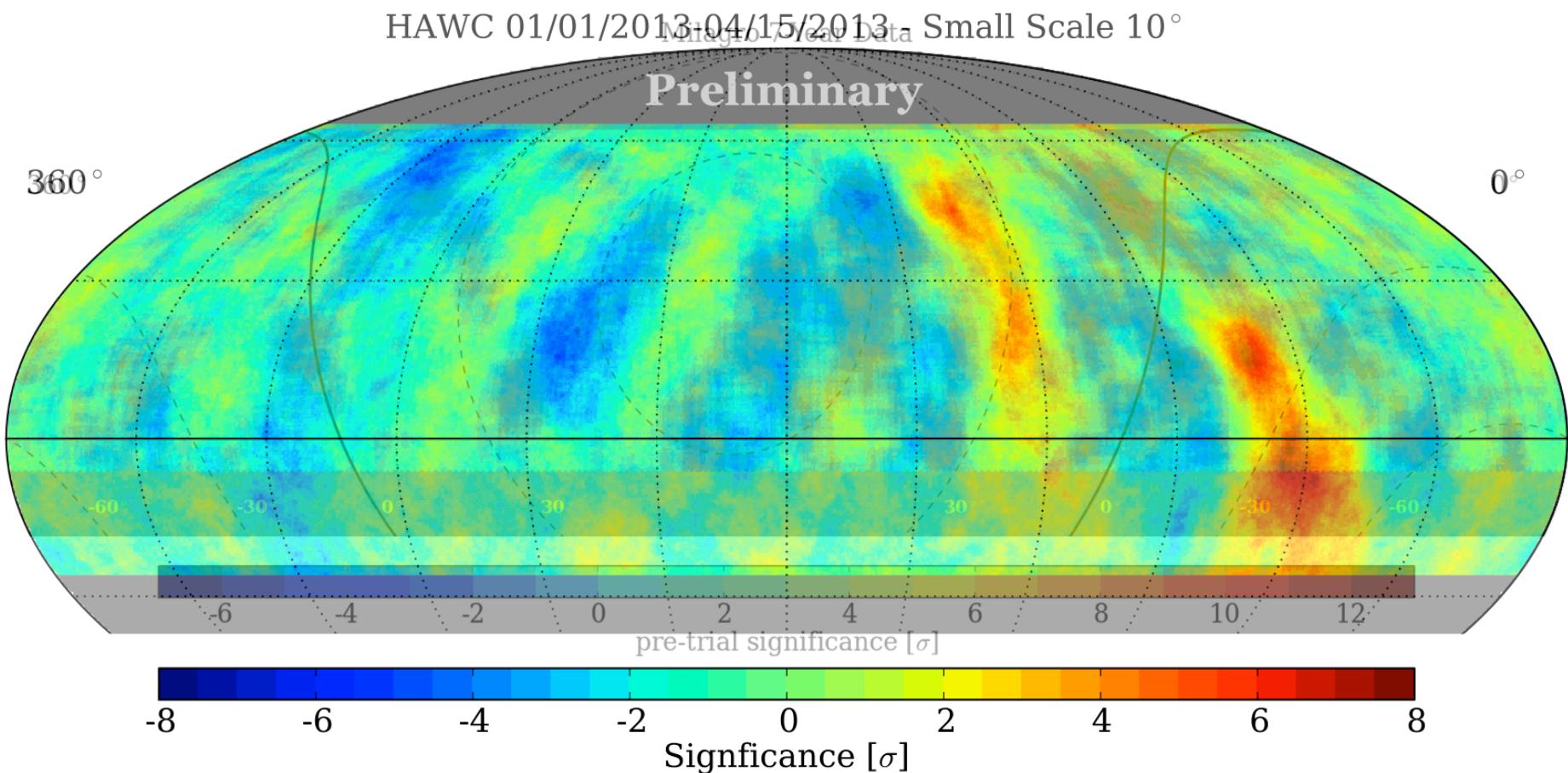
Comparison to Milagro Sky Map

- Milagro anisotropy: PRL 101:221101, 2008



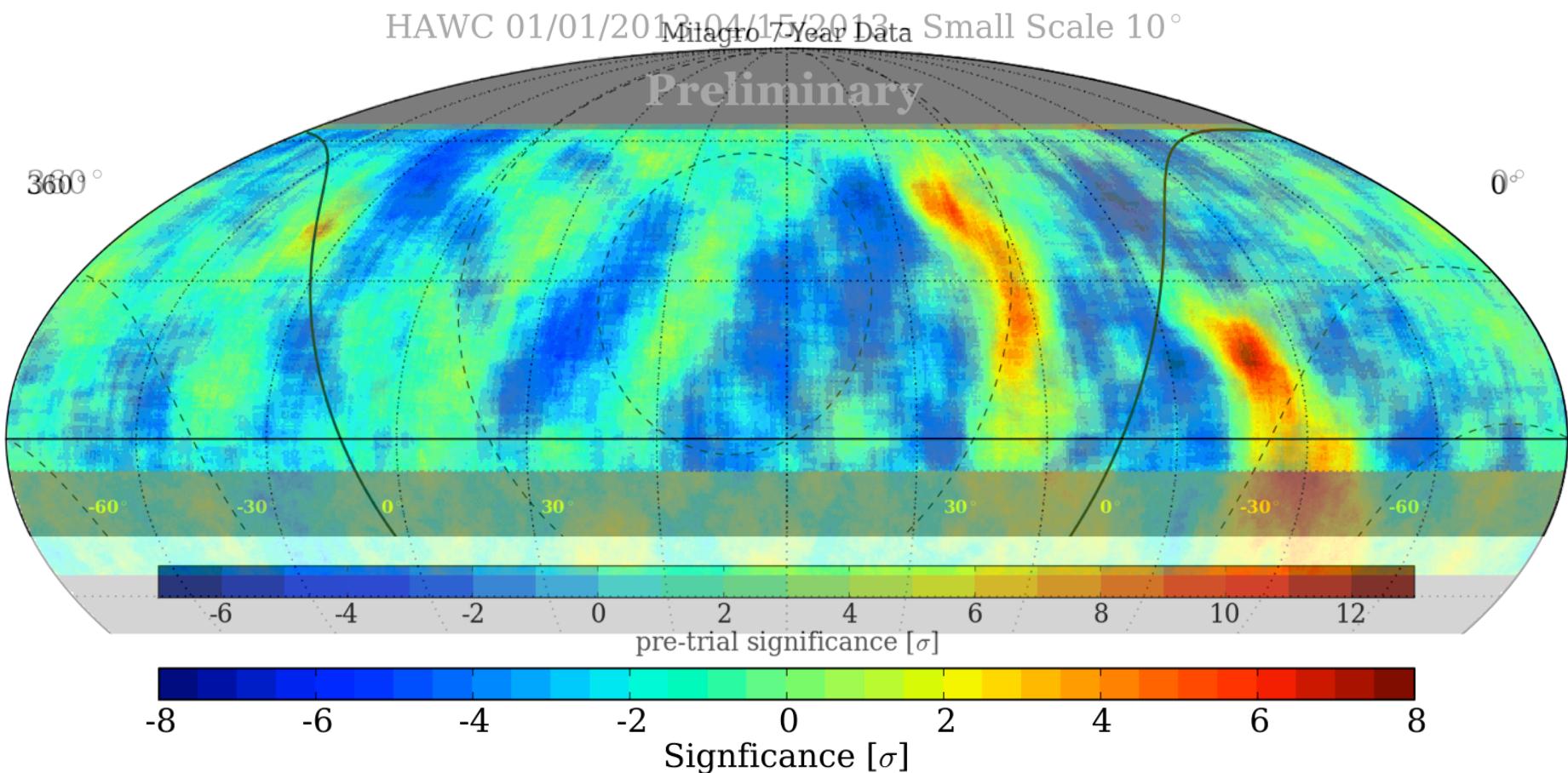
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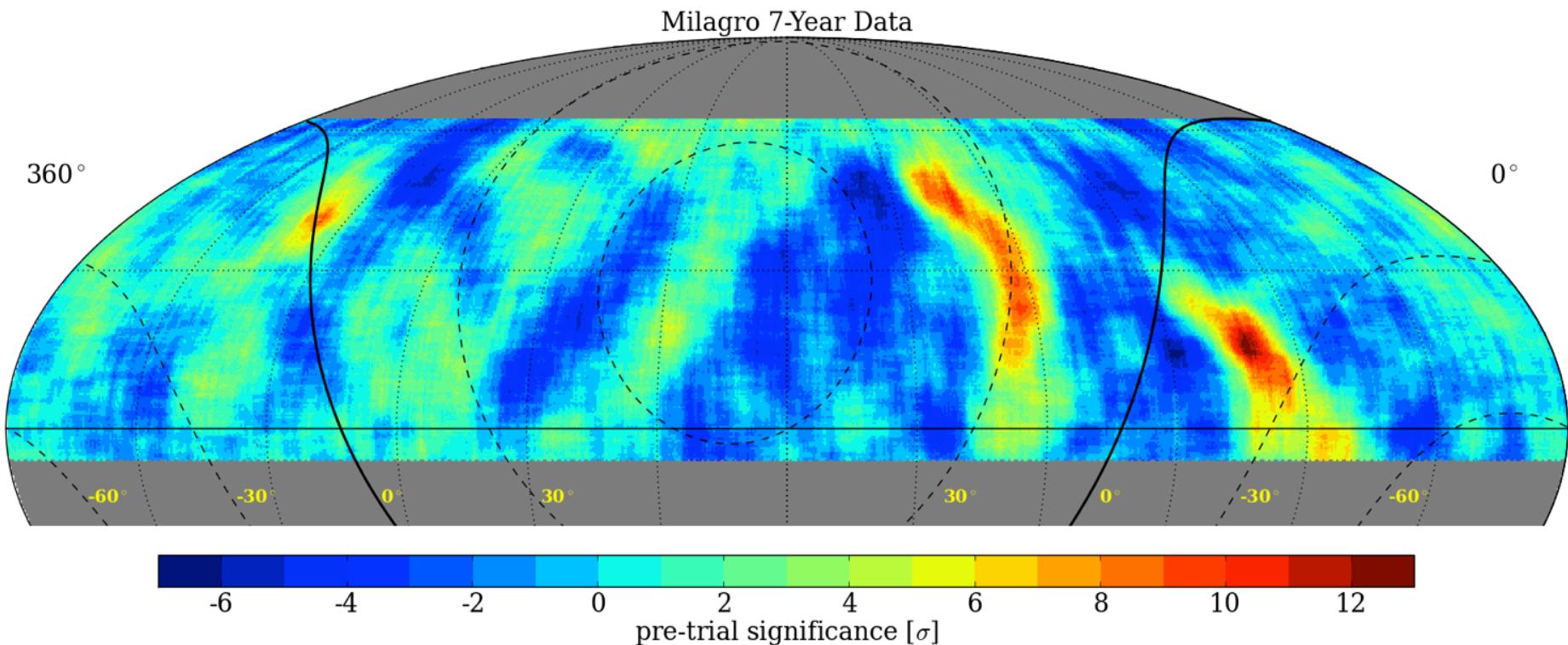
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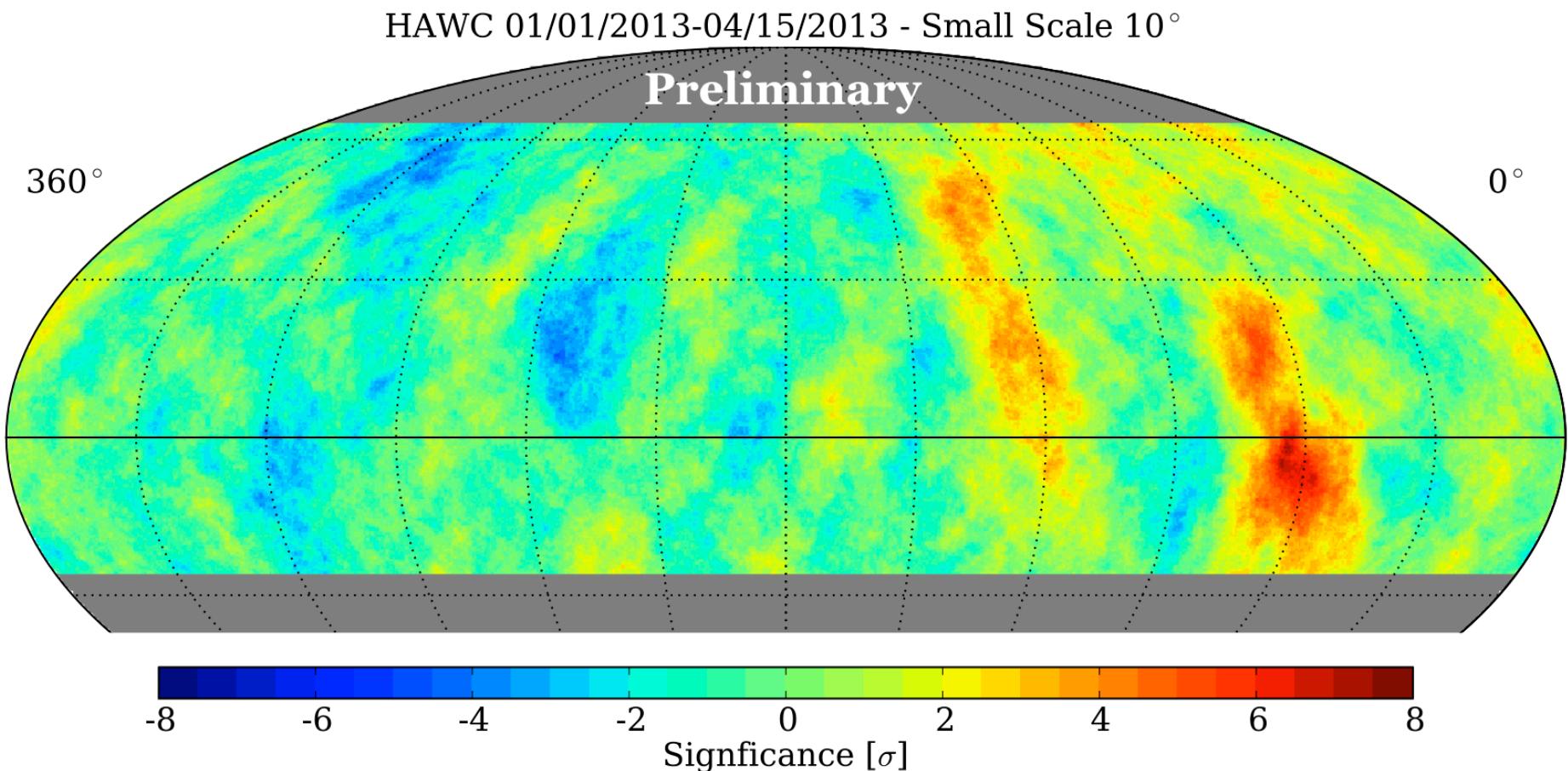
Comparison to Milagro Sky Map

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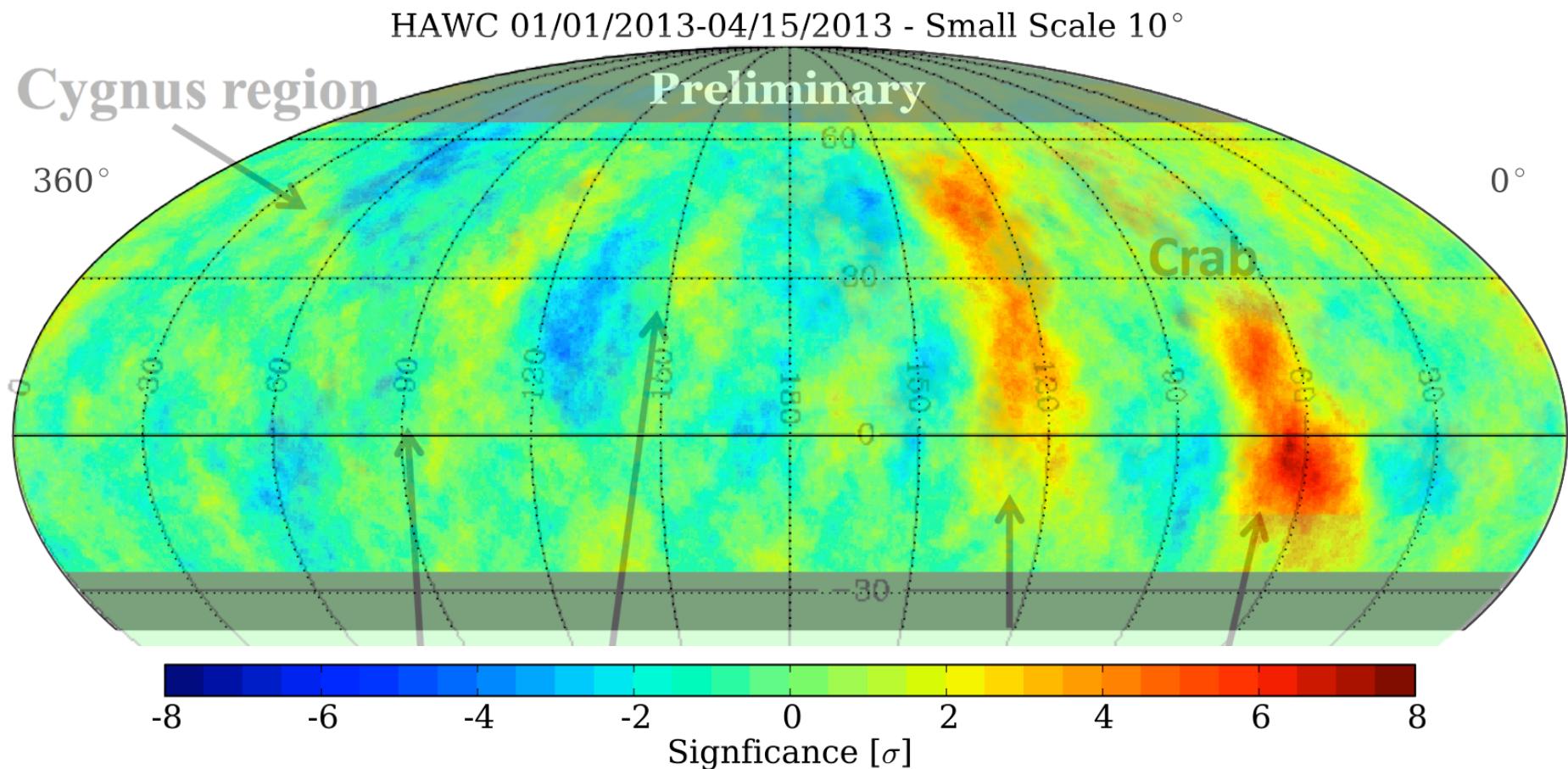
Comparison to ARGO-YBJ Sky Map

- ARGO anisotropy: G. Di Sciascio, ISVHECRI 2012



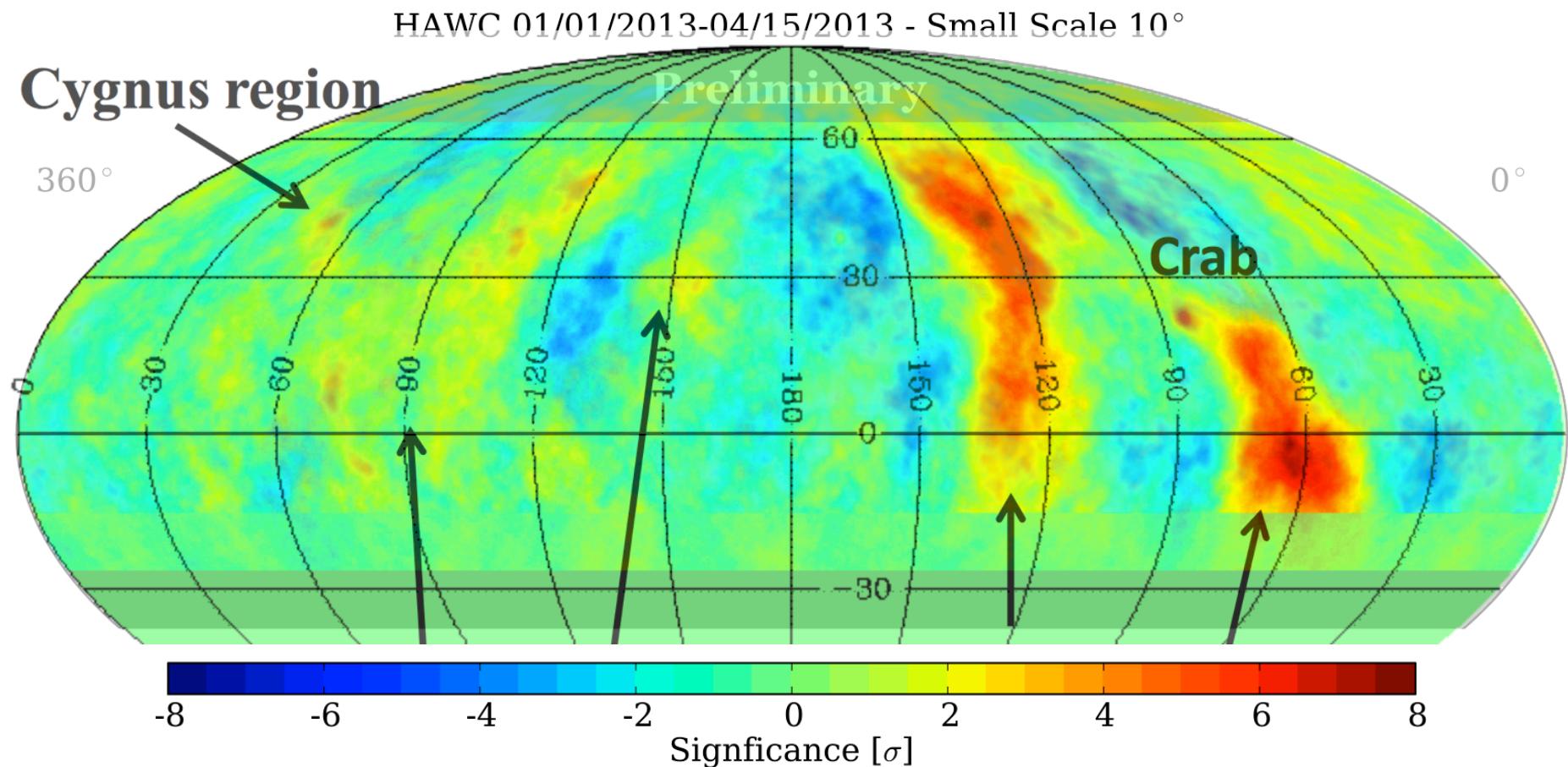
Comparison to ARGO-YBJ Sky Map

- ARGO anisotropy: G. Di Sciascio, ISVHECRI 2012



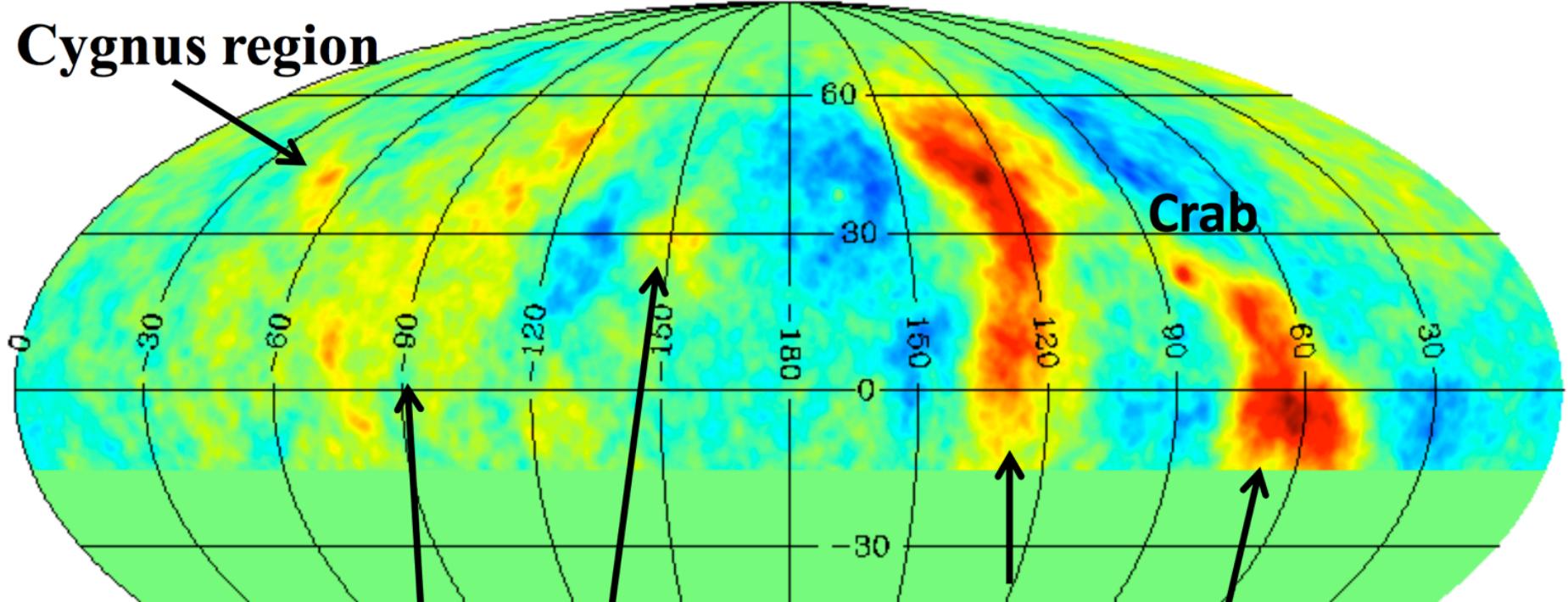
Comparison to ARGO-YBJ Sky Map

- ARGO anisotropy: G. Di Sciascio, ISVHECRI 2012



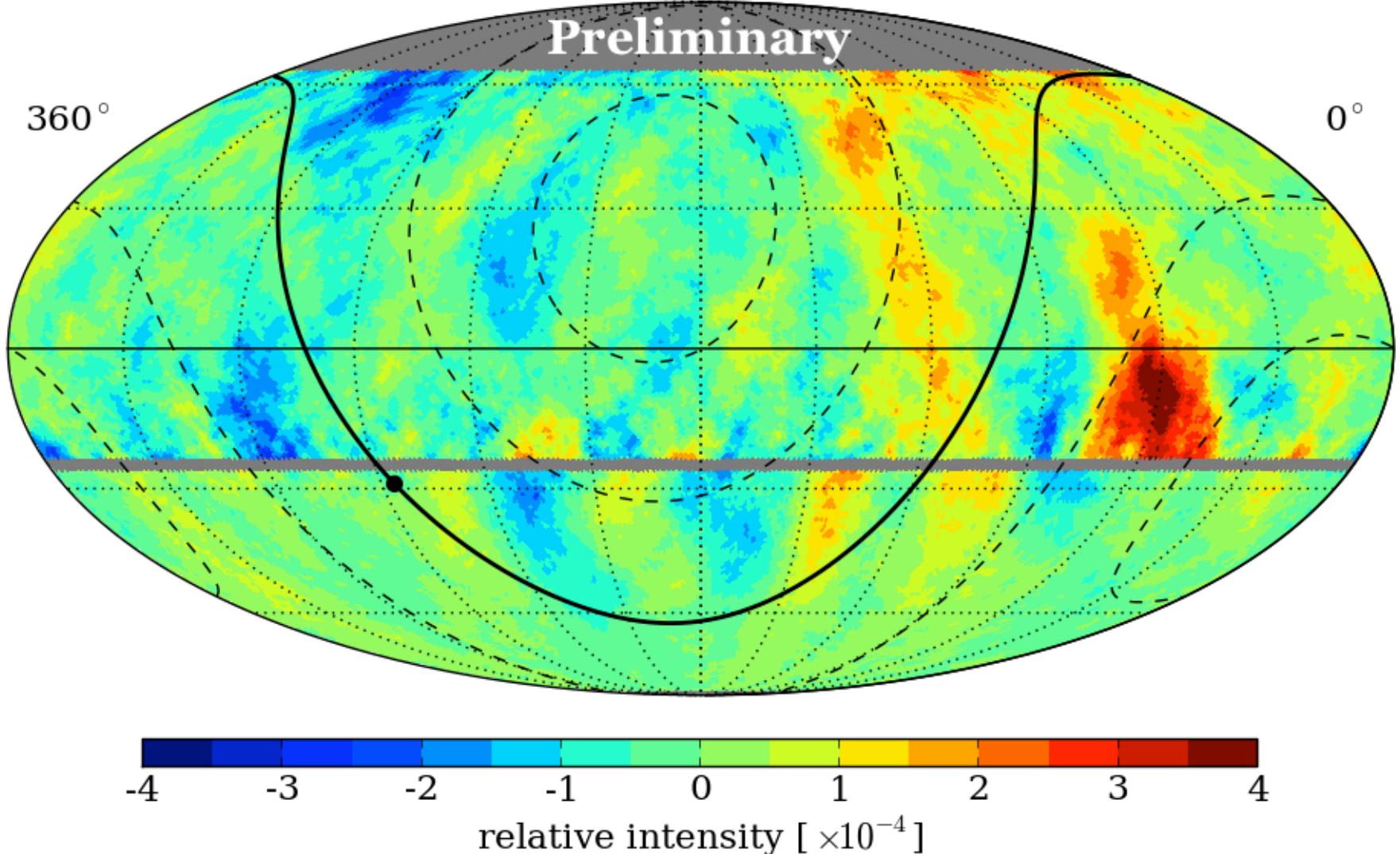
Comparison to ARGO-YBJ Sky Map

- ARGO anisotropy: G. Di Sciascio, ISVHECRI 2012



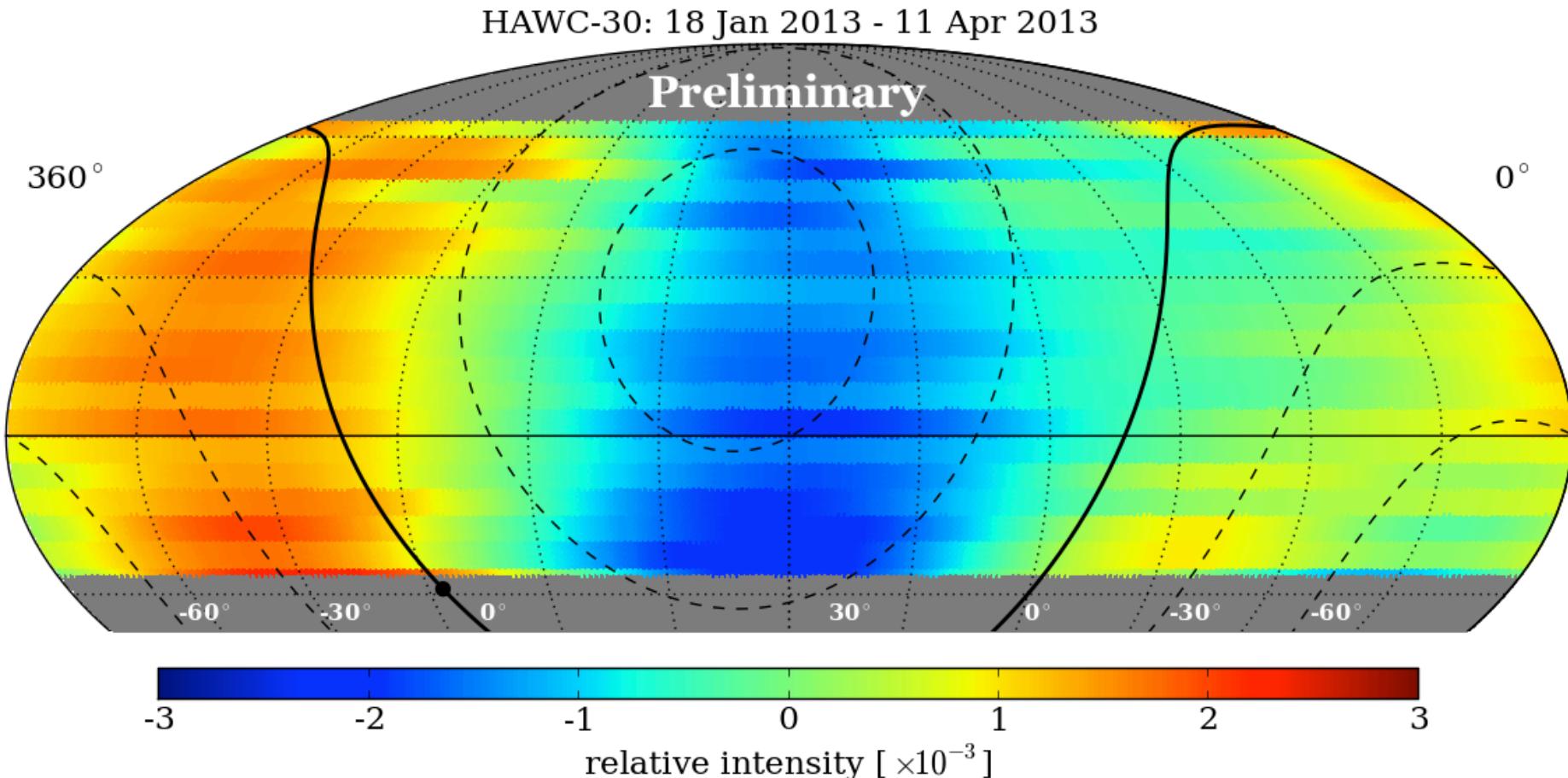
Comparison to IceCube

HAWC-30 (1 Jan - 15 Apr 2013) + IC-79: 10° Smoothing



Large-Scale Cosmic Ray Anisotropy

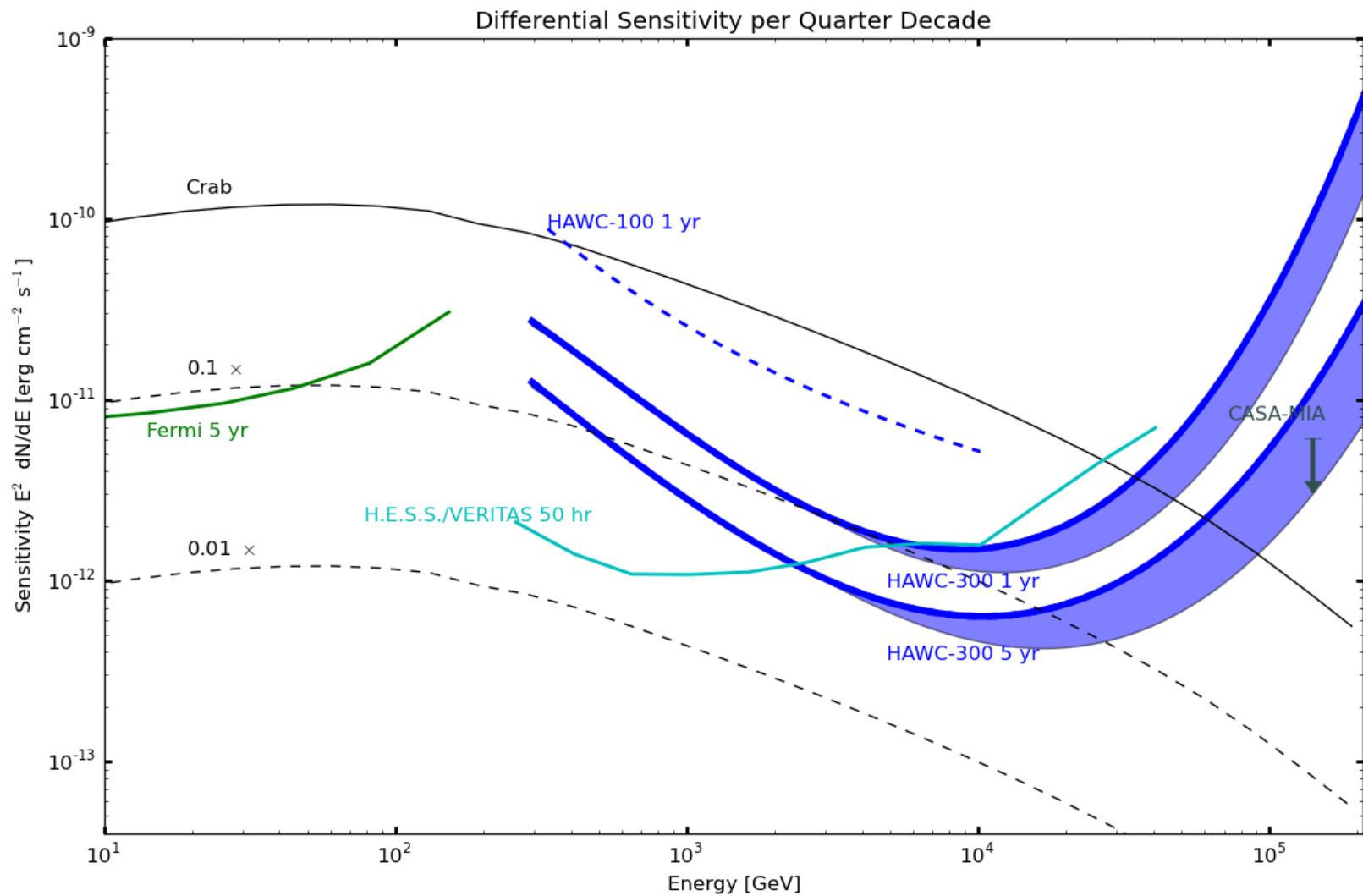
- Note: not a sky map, but a series of **3-term harmonic fits** within 18 declination bands



Conclusions

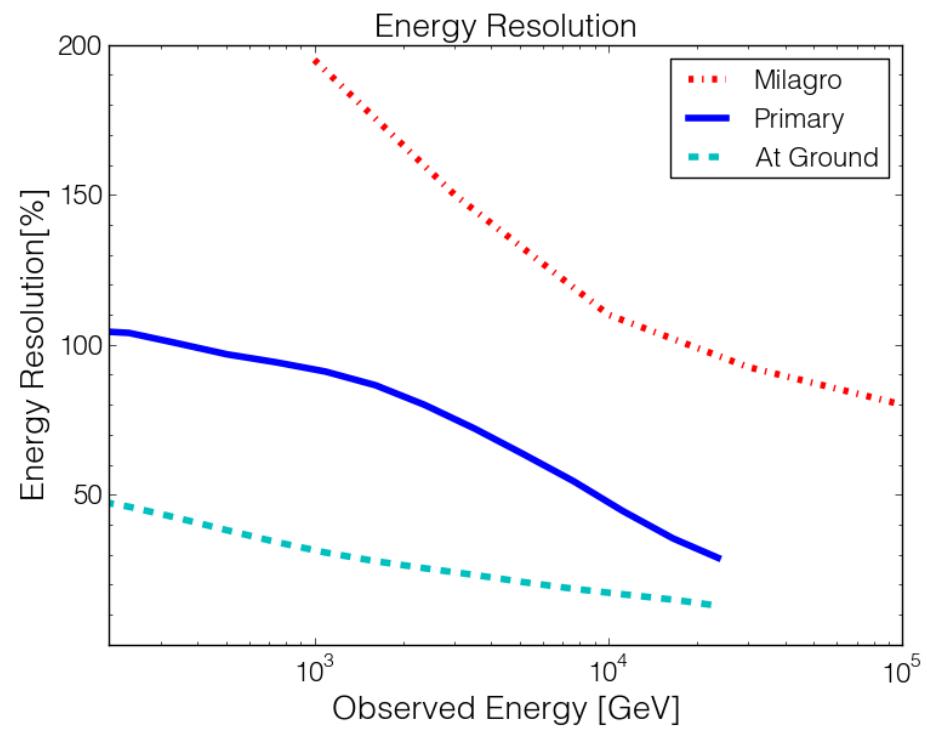
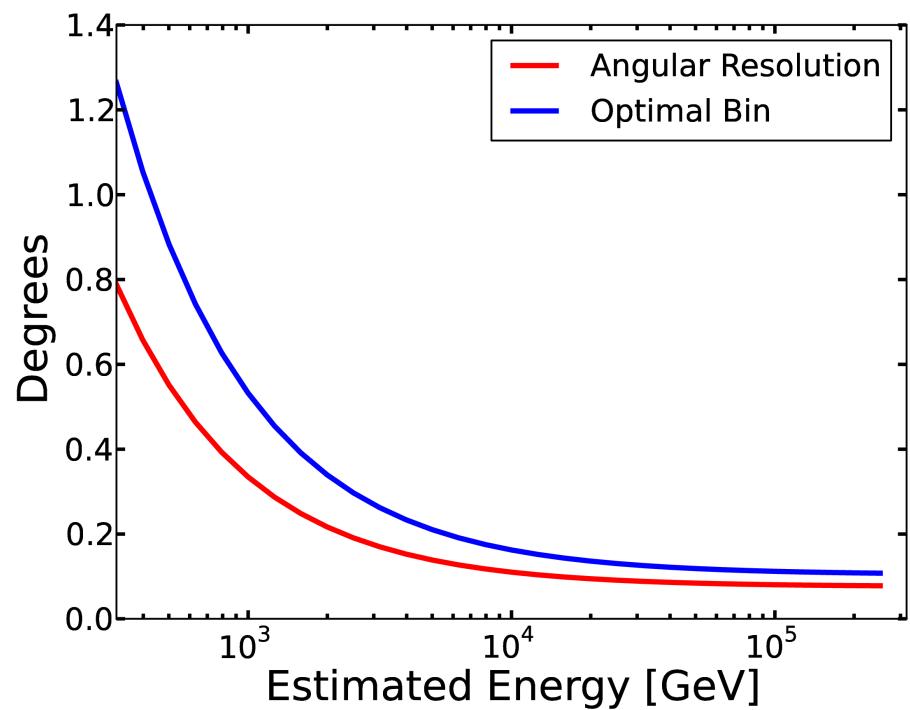
- HAWC is under construction and is currently **33% complete**
- We have analyzed **all data from HAWC-30** and some data from HAWC-95. Measurements include:
 - Significant anisotropy of cosmic rays: large- and small-scale
 - Lunar and solar shadows in cosmic rays
 - Solar physics: Forbush decreases, ground-level enhancements
 - Crab Nebula: below expectation; calibration pending
- Next year, HAWC construction will end. Expect to see:
 - Observations of emission from point-like and extended sources
 - Our first measurement of the galactic diffuse emission
 - Observations of transients: AGN and GRBs (if bright enough)
 - Indirect dark matter limits $> 1\text{-}10 \text{ TeV}$ (**talk by J.P. Harding**)
 - **The unexpected...**

Sensitivity to Point Sources



HAWC-300 Performance

- Angular resolution and energy resolution



Analysis: Small-Scale Anisotropy

- Search for anisotropy in arrival directions with binned **relative intensity** of the cosmic rays:

$$\delta I_i(\alpha, \delta) = \frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha, \delta) - \langle N_i(\alpha, \delta) \rangle}{\langle N_i(\alpha, \delta) \rangle}$$

- Apply **direct integration algorithm** to calculate isotropic “reference map” from the data:

$$\langle N(\alpha, \delta) \rangle = \int dt \int d\Omega A(ha, \delta) \cdot R(t) \cdot \epsilon(ha, \alpha, t)$$

rate 1 if ha, α, t in same bin
acceptance

- Exposure length dt acts as a **high-pass filter** on structure $> 15^\circ \text{ hr}^{-1} \times dt$

Large-Scale Analysis

- Need to account for **non-uniform exposure** due to shadowing by horizon, plus detector variations
- Various methods available for this: east/west, equi-zenith, forward-backward, etc.
- Apply **forward-backward method** used in A. Abdo et al., *Astrophys. J.*, 2009, **698**: 2121
- Assume intensity in declination band δ can be written

$$I_\delta(\alpha) = \frac{R_\delta(\alpha)}{\langle R_\delta(\alpha) \rangle} = 1 + \sum_{n=1}^3 A_{n,\delta} \cos n(\alpha - \varphi_{n,\delta})$$

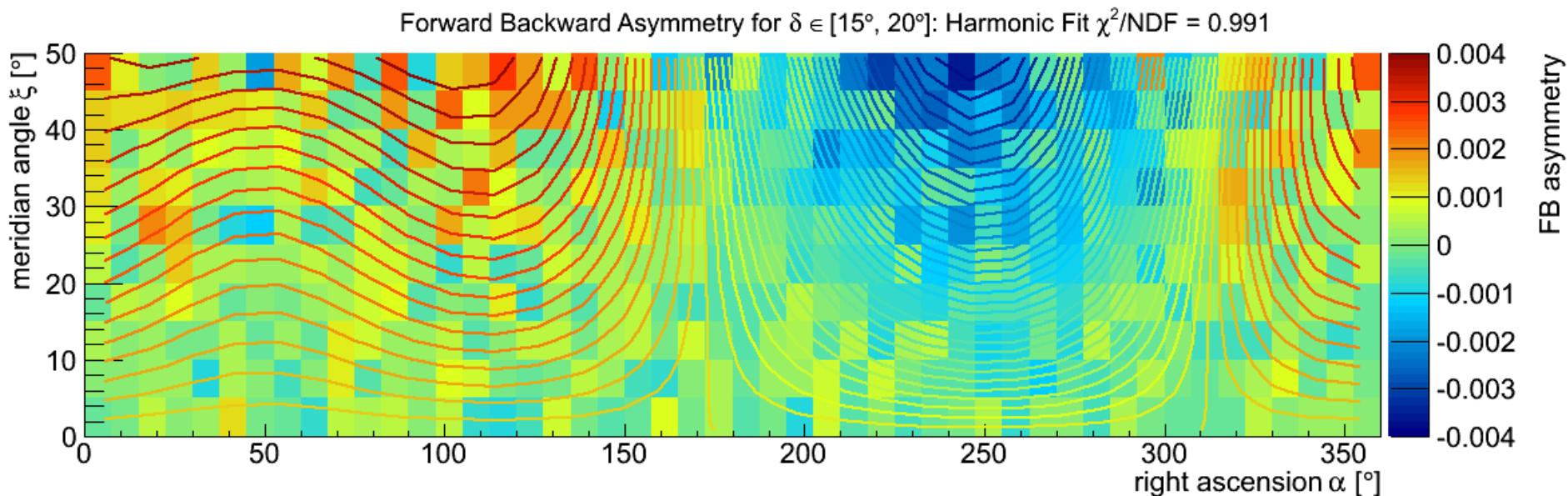
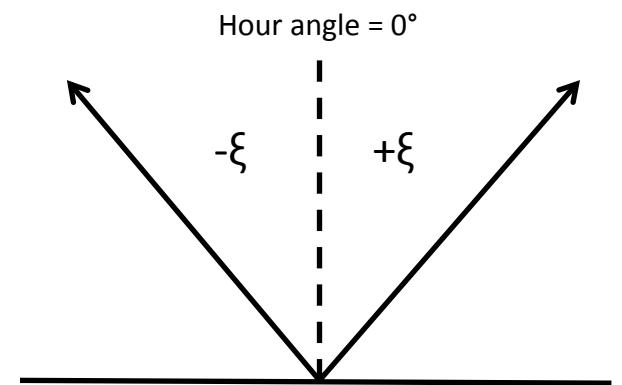
Forward-Backward Harmonic Fit

- Relative counts w.r.t. local meridian:

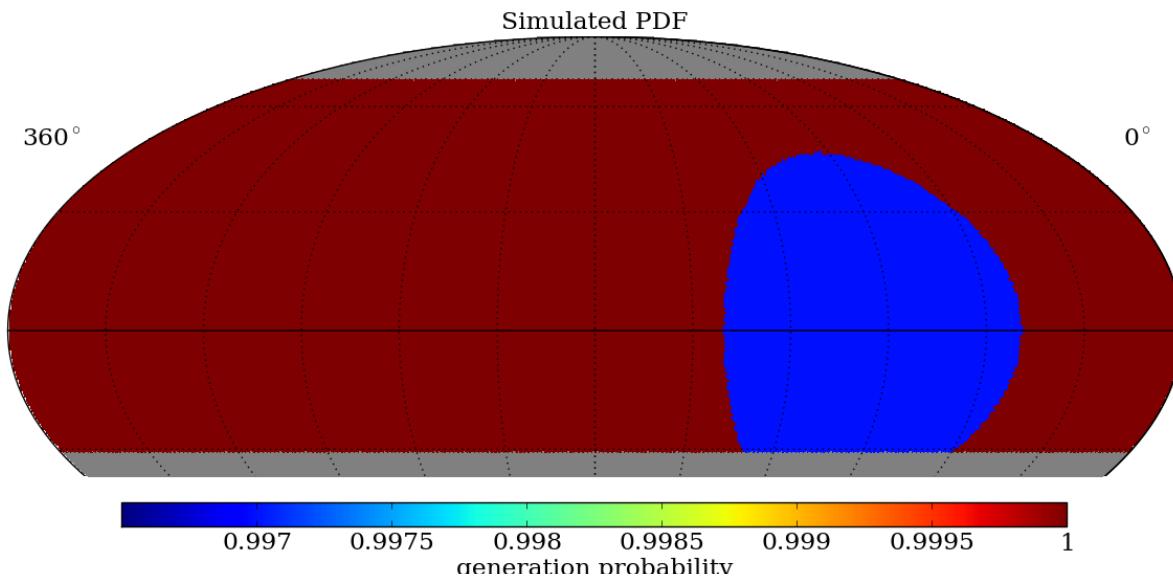
$$FB(\theta_0, \delta) = \frac{N_{\theta_0, \delta}(+\xi) - N_{\theta_0, \delta}(-\xi)}{N_{\theta_0, \delta}(+\xi) + N_{\theta_0, \delta}(-\xi)}$$

- Three-term harmonic fit:

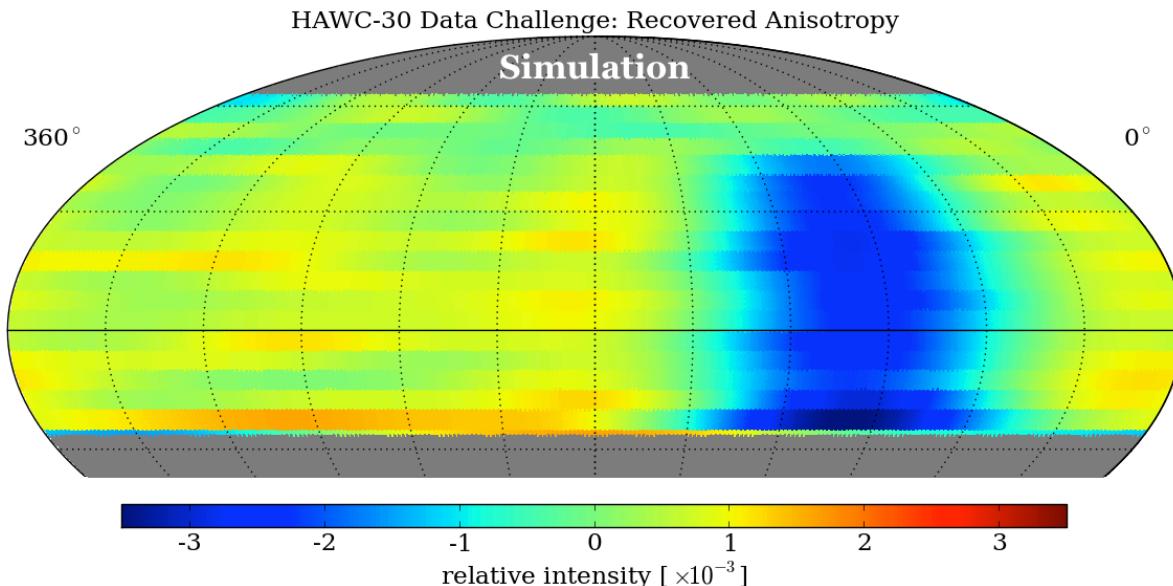
$$FB_\delta(\theta_0, \xi) \approx \sum_{n=1}^3 -A_{n,\delta} \sin(n\xi) \sin(n(\theta_0 - \varphi_{n,\delta}))$$



Large-Scale FB “Data Challenge”

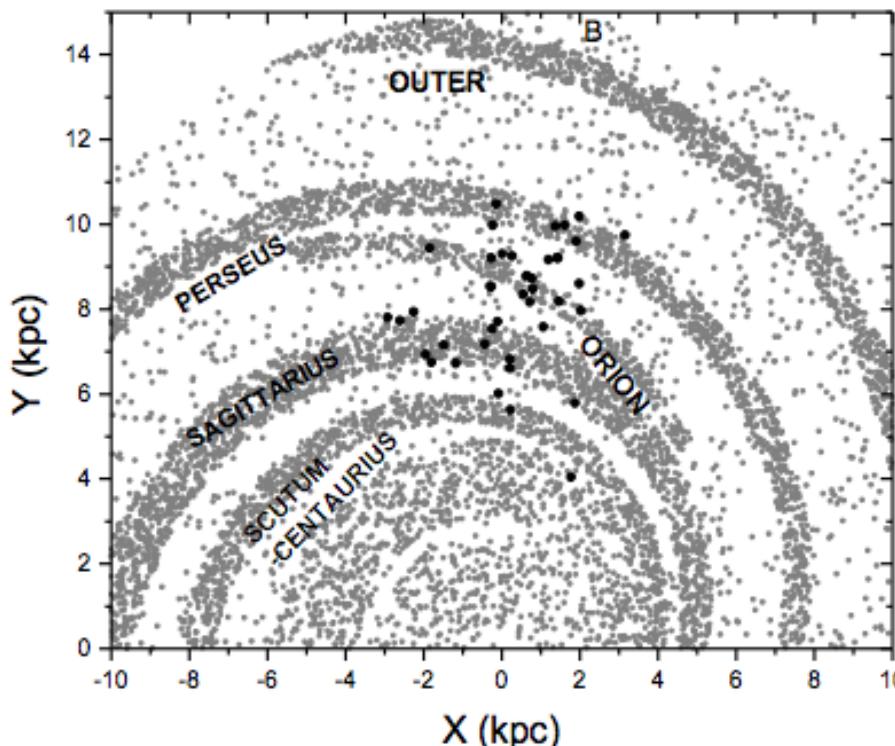


- **Simulation:** isotropic background with a 3×10^{-3} top-hat deficit
- **Recovered anisotropy:** harmonic fits in 18 declination bands



Origin of Large-Scale Anisotropy?

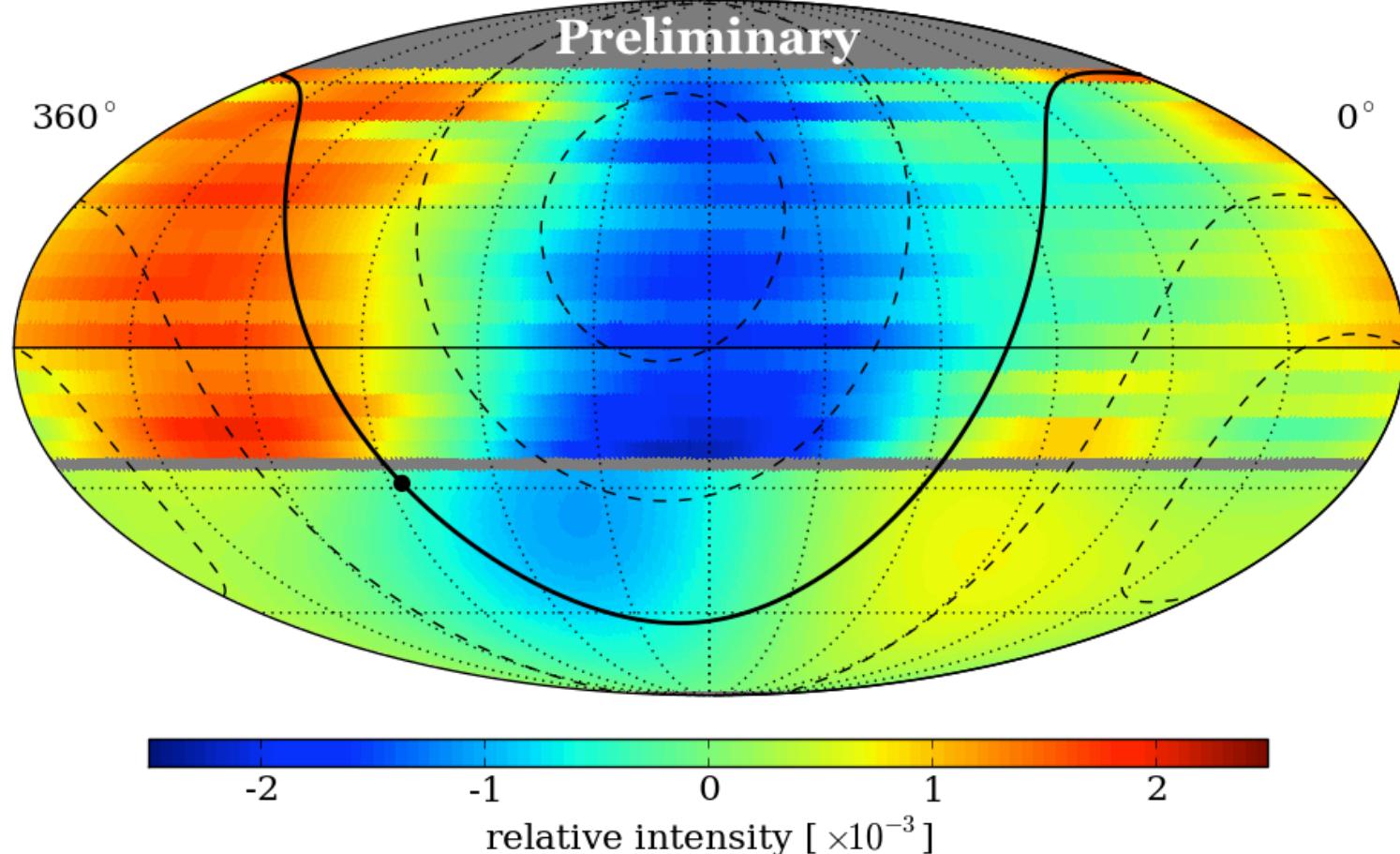
- Larmor radius of 10 TeV proton in Galaxy: ~ 0.01 pc
- But, $\sim 10^{-3}$ anisotropy arises even with diffusion
- “Dipole” anisotropy comes from nearby sources



See, e.g., Wolfendale
and Earlykin,
Astropart. Phys. **25**
183 (2006)

HAWC + IceCube Large Structure

HAWC-30 (18 Jan - 11 Apr 2013) + IC-79 Dipole+Quadrupole Fit



- Note disagreement in amplitude. This may be due to partial-year coverage of HAWC data

Dark Matter Sensitivity

